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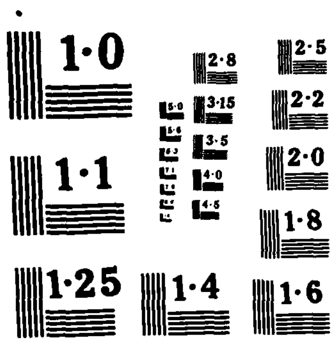

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DESIGN CONSIDERATIONS FOR AN ADVANCED TROPICAL CYCLONE MODEL

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OCTOBER 1985

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A project planning meeting on dynamical tropical cyclone models was held January 3-4 1985 at NAVENVPREDRSCHFAC to guide development of a next-generation forecast model, or Advanced Tropical Cyclone Model (ATCM). The meeting was structured in three groups: an Operational group (OP) to provide forecaster needs and real world constraints; a Numerical Aspects group (NUM) with expertise in the numerical modeling issues; and a Data Analysis and Initialization group (DAI) to guide the development of the data analysis and initialization component of the ATCM.

The OP group stated that an ATCM should provide the primary tropical cyclone track guidance in the 48-72 h range and that the model should predict wind distribution. It was emphasized that to achieve these goals successfully, the ATCM system must (1) analyze and predict synoptic-scale features adjacent to the tropical cyclone; (2) allow the user to specify the initial intensity and the horizontal and vertical structure of the tropical

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cyclone; (3) handle multiple storms; and (4) include topographic effects.

The NUM group recommended that the first version of the ATCM have uniform horizontal resolution (vice a two-way interactive, moving nested grid) of about 50 km, and a vertical resolution of about 10 layers. The domain size should be on the order of 9000 km (E-W) by 6000 km (N-S). Because the storm simulation ultimately will be governed by the physics in the model, it was recommended that a dynamical-physical interactive physics package be used with constraints to ensure a realistic representation of the vortex.

The DAI group agreed that the lack of an accurate and complete specification of the wind field in the environment of the tropical cyclone is the primary restricting factor in the performance of the dynamical models. Although existing analysis techniques may be adequate, the initial humidity fields will need special treatment and the storm circulation should be specified with a model-generated "bogus" storm.

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EXECUTIVE SUMMARY

The primary conclusions of the Planning Meeting on Dynamical Tropical Cyclone Models are summarized in this section. The background and supporting arguments for these conclusions are found in the main body of the report. The meeting was organized into three groups: 1) An Operational Group (OP) to provide forecaster needs and real-world constraints; 2) A Numerical Aspects (NUM) group with expertise in the numerical modeling issues for the design of a next-generation or an Advanced Tropical Cyclone Model (ATCM); and 3) A Data Analysis and Initialization (DAI) group to guide the development of the data analysis and initialization component of the ATCM.

The OP group set the following goals:

a. The primary goal of the ATCM should be to provide the primary tropical cyclone track guidance in the 48 h to 72 h range; and

b. The second goal of the ATCM should be to predict tropical cyclone wind distribution (e.g., radius of 30 kt and 50 kt winds and then intensity (maximum wind speed).

The OP group emphasized that to successfully achieve these goals the ATCM must take into account the following factors affecting tropical cyclones, and have these special features (by priority):

a. It will be necessary to accurately analyze and predict synoptic-scale features adjacent to the tropical cyclone.

b. The initialization of the ATCM must include a capability for the user to specify the initial intensity and the horizontal and vertical structure of the tropical cyclone.

c. The ATCM must be able to forecast interactions between two or more storms.

d. The ATCM should include a capability to forecast the effects of topography on the tropical cyclone.

The OP group also recommended that about 30 "classic" storms and 30 "high-interest" storms should be selected from two or three different seasons to form the validation sample.

The DAI group discussed several issues relating to the ATCM. Their conclusions and recommendations are summarized as follows:

a. The lack of an accurate and complete specification of the wind field in the environment of the tropical cyclone is considered to be the primary restricting factor in the performance of the dynamical models.

b. The Japanese should be encouraged to extract additional cloud-motion vectors throughout the viewing area of the Geostationary Meteorological Satellite, or to provide the images so that cloud-motion vectors can be determined by other countries.

c. Additional tasking of synoptic flight tracks in data-sparse regions around the storm is strongly recommended.

d. Inclusion of layer-mean, mid-tropospheric wind fields derived from geostationary satellite water vapors images would have an immediate positive impact on the accuracy of tropical cyclone track predictions.

e. Algorithm development should begin immediately to insure that the new computing capability to be available at Joint Typhoon Warning Center (JTWC) in 1986 will allow bogus wind and mass soundings to be transmitted to Fleet Numerical Oceanography Center (FNOC).

f. The most cost-efficient approach for developing an analysis for the ATCM would be to apply an optimum interpolation (OI) routine similar to that being developed for Navy Operational Global Atmospheric Prediction System (NOGAPS) and Navy Operational Regional Atmospheric Prediction System (NORAPS).

g. Early testing of the ATCM should be based on the Numerical Variational Analysis (NVA) until it can be demonstrated that a regional OI scheme provides similar or improved accuracy. Adjustment of the NVA analysis levels is also recommended to match observation levels.

h. Methods to specify the initial humidity fields for the ATCM must be developed and tested.

i. A special working meeting should be held at the appropriate time to address the specific data-checking and data-analysis routines required for the ATCM.

j. The inner core circulation ($r < 200$ km) must be specified by a model-generated "bogus" storm which takes into account the horizontal scale of the actual storm, and distinguish deep tropospheric cases from shallow or "sheared-off" tropical cyclones.

k. A pre-processing component is not recommended in the initial development because the planned improvements in data analysis and in the numerical model should reduce the need for such empirical procedures.

l. A nonlinear vertical mode initialization similar to that being developed for NORAPS should also be used for the ATCM.

m. The ATCM should run at t+8 to t+9 h after synoptic times to: 1) take advantage of late-arriving reports from the tropics; 2) receive bogus soundings from JTWC; and 3) use the most recent NOGAPS prediction for specification of lateral boundary conditions.

The NUM group also considered many issues related to the development of the dynamical model component of the ATCM. Their conclusions and recommendations are summarized below:

a. The first version of the ATCM model should have a uniform horizontal resolution (rather than a two-way interactive, moving nested grid) of about 50 km, and a vertical resolution of about 10 layers within the troposphere.

b. An appropriate domain size for the single storm situation is 7000 km (east-west) by 5000 km and 9000 km by 6400 (north-south) km for the multiple, and possibly interactive, storm situations.

c. The most recent NOGAPS forecast should specify time-dependent boundary conditions.

d. The NORAPS model should be adopted as the dynamical framework for the ATCM rather than pursuing an extensive intercomparison of recently developed research models.

e. Although a non-interactive heating distribution similar to the scheme used in the Naval Tropical Cyclone Model (NTCM) may be suitable initially, further progress will require parameterizations based on an explicit treatment of the dynamical-physical interactions between the tropical cyclone vortex and the convection.

f. Testing of topography effects in the ATCM model will be facilitated because NORAPS already accounts for orographic effects.

Finally, the participants at the Planning Meeting set relative priorities on the different aspects of the ATCM. The preliminary research plan (see Table 1) is intended as a guide for further internal discussions at NEPRF. Development of a detailed research plan and establishment of specific milestones must take into account availability of resources for this task in relation to the overall research program of NEPRF and the Navy research and development community.

1. Introduction

The primary motivation for the Planning Meeting was to achieve a scientific consensus on developing the next-generation tropical cyclone forecast system based on a dynamical model. Over the years, the barotropic (first generation) models have been extended to baroclinic (second generation) and eventually to nested, baroclinic models. The Nested Tropical Cyclone Model (NTCM), Movable Fine-Mesh Model (MFM) and Moving Nested Grid (MNG) models represent the present third-generation tropical cyclone track prediction models (see reviews by Elsberry, 1979; 1983). It appears that most of these later operational models were adapted from research models without considering the overall tropical cyclone prediction problem. It is now recognized that the dynamical model is just one component in this system.

The Planning Meeting was held at this time because it appears that the third-generation tropical cyclone models have reached a mature state. Although incremental improvements may continue to be made, it seems appropriate to now address the overall design of a next-generation system. In addition to advancements in numerical aspects, there is a new and greater appreciation of the importance of data-checking, objective analysis and initialization aspects for operational models. New observational systems are becoming available and significant improvements in forecast skill will very much depend on the ability of the dynamical forecast system to utilize all data. Last, but not least, there is an operational Department of Defense (DOD) requirement for improved tropical cyclone forecasts that calls for a reduction by one half of the current mean official forecast errors. In a recent letter, the Commander, Naval Oceanography Command (NOC) reiterated the need for meeting previously stated goals of tropical cyclone track accuracy. A tropical cyclone forecast system based on a next-generation dynamical model offers the best approach for achieving these DOD requirements.

It is useful to emphasize the time constraints for developing a strategy and for demonstrating an improvement in forecasts. The operational units such as Joint Typhoon Warning Center, Guam (JTWC) are under considerable (immediate) pressure to improve their warnings. Although the proposed next-generation dynamical system is just one effort by the research and development groups, it must be a timely effort if it is to receive the endorsement and support of the DOD community. Thus, the Planning Meeting was scheduled before the Typhoon

Conference of February 1985 so that a progress report could be given at that meeting. This report will be distributed as early as possible to inform DOD interests of the consensus reached on the scientific basis for developing the next-generation system.

The participants (see list in Appendix A) were divided into three groups: Operational (OP); Numerical (NUM) and Data Analysis and Initialization (DAI). Because only two days were available (see Agenda in Appendix B), much of the background material had to be prepared and circulated prior to the meeting. These materials included: (a) a position paper on operational considerations (Appendix C) by LCDR S. Sandgathe, USN (Deputy Director, JTWC); (b) research objectives endorsed by the Environmental Group of the Pacific Command; (c) an evaluation by JTWC of the NTCM during 1984; (d) a description of the U.S. Navy tropical analysis and the Naval Operational Global Atmospheric Prediction System (NOGAPS) analysis (Appendix E); (e) a review of the U.S. Navy dynamical tropical cyclone models (Appendix F) by M. Fiorino of Naval Environmental Prediction Research Facility (NEPRF); (f) a strawman proposal for an Advanced Tropical Cyclone Model (ATCM) (Appendix G) prepared by R. Elsberry of the Naval Postgraduate School (NPS); (g) a list of about 60 issues (Appendix H) that were addressed in group and planning sessions.

The initial focus of the meeting was on operational needs, capabilities and constraints. In addition to the keynote operational presentations by LCDR Sandgathe, USN, CAPT H. Nicholson, USN (Commanding Officer, Fleet Numerical Oceanography Center, FNOC), C. Mauck (FNOC) described the computer resources and operational computer constraints on the proposed system. A second keynote presentation by M. Fiorino summarized the status and problem areas in the present model. These were followed by brief presentations on related research and operational efforts by other agencies (Naval Research Laboratory, S. Chang; National Hurricane Center (NHC), A. Pike; National Meteorological Center (NMC), M. Mathur; and Colorado State University (CSU), W. Gray). The remainder of the meeting was devoted to group sessions. The NUM, DAI and OP groups were chaired by R. Anthes (National Center for Atmospheric Research, NCAR), J. Lewis (Cooperative Institute for Meteorological Satellite Studies, CIMSS - National Oceanographic and Atmospheric Administration, NOAA) and CAPT J. Tupaz, USN (Deputy Commander, NOC). Valuable assistance was provided by the rapporteurs J.C.L. Chan (NPS), J. Peak (NPS), S. Sandgathe and M. Fiorino.

The next section summarizes the results of the meeting. Although there are overlapping areas, the general order of presentation is along functional lines of the operational data stream, i.e., data input, model run and output.

2. Operational Considerations

A point paper (Appendix C) was provided to familiarize the participants with the forecast problem from the Joint Typhoon Warning Center's perspective. It was intended to serve as a starting point for discussion of operational requirements and constraints on the ATCM. The operational group restated the goals as follows:

a. The primary goal of the ATCM should be to provide tropical cyclone track guidance in the 48 hour to 72 h range.

Discussion: The primary purpose of the ATCM is to provide guidance to the forecaster at track "decision points." Consistency in performance from forecast to forecast is an important factor. Even if the model is consistently wrong for reasons that the forecaster can infer based on knowledge of the model and the present situation, the model will still have "forecast content." Because this consistency factor is established separately for each storm, it would be desirable to initiate ATCM forecasts on tropical disturbances that may become named storms during the next 24-36 h. Forecast tracks may have to be extended to 84 h to provide longer guidance for the 72 h forecast because of the approximately nine hour delay beyond synoptic times before the ATCM forecasts will be received by JTWC.

b. The second goal of the ATCM should be to predict tropical cyclone intensity and wind distribution.

Discussion: It is very unlikely that the dynamical model is the appropriate method of forecasting the maximum wind speed or minimum surface pressure. However, the horizontal distribution of the wind field is the crucial product for the military customers. That is, the primary purpose of the track forecast is specify the dangerous wind regions. A potentially realizable goal is to predict the radius of 30 kt and 50 kt winds at 24 h and the radius of 30 kt winds at 48 and 72 h.

The operational group emphasized that to achieve these goals the ATCM must account for the following factors affecting tropical cyclones and have these special features:

a. It will be necessary to analyze and predict synoptic-scale features adjacent to the tropical cyclone.

Discussion: In the western North Pacific and Indian Ocean regions, the interaction of the tropical cyclone with the monsoons is an essential factor. Disturbances may intensify to typhoon stage while remaining within the monsoon trough. In these cases, a well-defined basic current either does not exist or cannot be resolved by the observations. As a result, forecasts from the objective aids tend to be very poor. The ATCM should also be able to forecast situations in which an existing tropical cyclone interacts with a strongly sheared monsoonal flow. Adjacent synoptic features, such as narrow ridges poleward of the tropical cyclone or tropical upper tropospheric trough (TUTT) lows, are at present, not adequately resolved in the tropical analyses. The track of the tropical cyclone may deviate significantly from the larger-scale steering during periods of interaction with these adjacent synoptic features. Thus, it is a high priority item that these features be bogussed into the tropical analyses if they are not resolved by available observations.

b. The initialization of the ATCM must include a capability for the user to specify the initial intensity and the horizontal vertical structure of the tropical cyclone.

Discussion: A wide variety of intensities and scales of the tropical cyclone wind structure must be accommodated. The ATCM must be able to provide early guidance for tropical disturbances that may come into a warning status. Vertical structure of the tropical cyclone is also very important. Shallow (below 700 mb) circulations with typhoon intensity exist and are not well-predicted by a model that assumes all tropical cyclones have a deep tropospheric structure. "Shearing-off" of the convection by strong upper-level flow can result in difficult forecast situations. Horizontal scale differences among tropical cyclones can lead to different basic current-vortex motion relationships. Typhoon [illegible] during 1984 had a radius of 30 kt winds of 100 n mi, whereas the circulation of other typhoons such as ABBY during 1983 may cover much of the western North Pacific region.

c. The ATCM must be able to forecast interactions between multiple storms.

Discussion: Interaction between two tropical cyclones occurred for about 1/3 of the storms in the western North Pacific during the 1984 season. The forecaster has little guidance on how storm interaction will affect the track of each cyclone or whether one storm will be absorbed by the other.

Multiple storm situations (not necessarily interacting) exist on average about 120 days during the year and present special analysis and boundary condition problems for the dynamical models. Therefore, the planning for the ATCM should consider the multiple storm situation.

d. The ATCM should include a capability to forecast the effects of topography on the tropical cyclone.

Discussion: The present U.S. Navy dynamical models do not include the effects of land surfaces or interaction with topography. Better guidance is needed when the cyclone track is significantly influenced by the terrain.

Tropical cyclone research by the U.S. Navy has been directed toward the western North Pacific region, which is a key operational area. The National Weather Service (NWS) is responsible for the Atlantic and the eastern North Pacific regions. Thus, the ATCM effort will be focussed on the western North Pacific area, including the South China Sea. Less priority will be given (in descending order) to the Arabian Sea, Australian region, the South Indian Ocean and the Bay of Bengal. Although improvement in tropical cyclone forecasts in the these areas is desirable, the location of DOD assets dictates that the primary emphasis should be in the western North Pacific region.

3. Data Analysis and Initialization Issues

A. Data Considerations

1. Existing data. The lack of an accurate specification of the wind field in the environment of the tropical cyclone is considered to be the primary restricting factor in the performance of the dynamical models. As indicated in Appendix C, the data available in the different typhoon basins vary considerably. Although there are portions of the western North Pacific region that have reasonable rawinsonde coverage, these observations are typically made once per day. The primary tropical cyclone genesis area to the east of the Philippines is devoid of rawinsondes over about a 20° latitude square. The DAI group reviewed the frustration of having minimal cloud-motion vectors from the Japanese geostationary satellite unless a typhoon is approaching Japan. Because a private agency in Japan produces and transmits these vectors, the solution is mainly financial. The Japanese should be encouraged to extract additional cloud-motion vectors throughout the viewing area of the GMS, or to provide digital data so that cloud motion vectors can be determined by other countries.

The primary data levels in the tropics are near-surface and at jet aircraft flight levels. In some cases, the blend of conventional data (ships, aircraft and rawinsondes) and satellite cloud-motion vectors at these levels provide a reasonable representation of the environmental flow around tropical cyclones. The coverage, however, is not uniform in space or in time.

Aircraft reconnaissance observations are concentrated in the inner core (r < 200 km) of the storm. With the horizontal and vertical resolution of present and planned dynamical models, only limited direct use of these data is possible. Additional tasking of synoptic flight tracks in data-sparse regions before the storm is strongly recommended.

2. Future sources. The U.S. Air Force is presently upgrading the instrumentation and communication capability of its reconnaissance aircraft. The Improved Weather Reconnaissance System (IWRS) will make observations at a very high temporal rate and have the capability of direct data transmission via satellite. Unfortunately, the satellite down-link is to Hawaii and to the Philippines rather than to Guam. If these observations were also available on Guam, they would provide an important source of data for continually updating the storm-scale circulation fields.

The computer resources of the Naval Oceanography Command Center (NOCC)/JTWC, Guam will be significantly upgraded in mid-1986 (Appendix D). The NEDN (Naval Environmental Data Network) Oceanographic Data Distribution and Expansion System/Satellite Processing and Display System (NODDES/SPADS) will provide an interactive analysis capability that can be used to blend conventional and satellite observations. The stand-alone capability of this device also offers a potential for some sophisticated local analyses. Finally, the package will also include a high-speed, wide-band communication link to FNOC which will allow a real-time input to the FNOC analyses. Algorithm development should begin immediately to insure that an interactive capability is available at JTWC so that bogus soundings may be transmitted to FNOC.

An exciting new data source in the mid and upper troposphere over the oceans has recently been demonstrated. Dr. K. Hayden at CIMSS/NOAA in Madison, WI has shown that layer-average wind vectors representative of mid-tropospheric flow can be derived from the water vapor channels onboard the Geosynchronous Operational Environmental Satellite (GOES). These observations in clear air can be combined with lower and upper tropospheric cloud-motion vectors to analyze a more complete representation of the three-dimensional wind field (J. Lewis,

personal communication). About 1.5 hours on an interactive graphics display unit is required to infer wind vectors from a sequence of three water vapor channel images that are separated by one hour. Thus, there is operational potential in this new data source. The consensus of the NUM group was that inclusion of these layer-mean, mid-tropospheric wind fields would have an immediate positive impact on the accuracy of tropical cyclone track predictions.

The omega dropwinsonde (ODW) program at the Hurricane Research Division (HRD/NOAA) has successfully supplied data in real time around Atlantic hurricanes on several occasions (Burpee et al., 1984). When two aircraft are utilized, the data coverage is especially effective in representing the environmental wind field. S. Lord of HRD is applying a function fitting objective analysis scheme of V. Ooyama (HRD) to these wind fields. A two-scale approach is used. The large-scale analysis provides the background fields and a smaller scale analysis is then made over the domain of the ODW soundings to improve the wind field around the storm. Such an ODW program can be cost-effective for improving landfall forecasts on the United States coast. It is unlikely, however, that this ODW capability will exist in the western North Pacific or any other tropical cyclone basin in the near future, although the Air Force IWRS will allow this capability.

A potential source of surface winds near tropical cyclones will be available in mid-1989 from the Navy Remote-Sensing Oceanographic Satellite System (N-ROSS). FNOC will be the primary processing center for these observations. There will be spatial and temporal gaps in the swaths of wind vectors over the tropical regions. Furthermore, additional research is necessary to develop data assimilation techniques that will extend the impact of the surface data into the upper levels.

Finally, the development and application of wind profilers offers a long-range source for improved observations of tropical circulations. The nearly continuous time resolution and unattended operation of these profilers are just two benefits that will lead to their eventual operational implementation. The time frame, however, is well beyond that of the present project.

B. Analysis Considerations

There are presently several objective analysis routines at FNOC and NEPRF which might be used to provide the initial conditions for the ATCM (Appendix E). The One-Way Influence Tropical Cyclone Model (OTCM) and NTCM are driven by the Numerical Variational Analysis (NVA). Fiorino describes a test in which the NTCM was driven with the NOGAPS initialized wind field (Appendix E). The overly strong zonal flow in these early NOGAPS fields was likely due to the initialization procedure. Implementation of a nonlinear normal mode initialization in NOGAPS should reduce the "sloshing" within the tropics during the data assimilation cycle. When these short-term oscillations are removed from the first-guess fields, the tolerances on the data rejection criteria can be tightened. The initialized fields should then agree more closely with the observations, as well as be consistent with the forecast model.

The primary analysis problem in the tropics is a lack of observations to represent the synoptic circulations. Given sufficient observations there are only small differences among the resulting fields from the various objective analysis routines. Without observations, the analyses tend to return the first-guess values. In the case of the NVA, the first guess is the previous analysis with a slow return to a monthly wind climatology. In NOGAPS, the first guess is a 6 h forecast and in data-sparse regions this first guess will include a strong "model climatology" component.

An optimum interpolation (OI) analysis scheme for NOGAPS will be evaluated at FNOC during 1985. Furthermore, a regional OI analysis code is being developed to support the Navy Operational Regional Atmospheric Prediction System (NORAPS) over the Mediterranean. The present NORAPS analysis is a Barnes-type successive correction routine patterned after the present NOGAPS analysis. NEPRF and FNOC seek to minimize the number of analysis routines because of the expense and difficulty in supporting a multitude of software packages in the operational system. Thus, the most cost-efficient approach for developing an analysis for the ATCM would be to apply a OI routine similar to the one used in NOGAPS and NORAPS.

The new analysis should be run in parallel with the NVA for several reasons. First, a considerable time period will be necessary for the development of an acceptably accurate OI analysis for regional application in the tropics. A participant from NOAA pointed out that the NMC global OI required

over a decade to develop. Although the development of the regional OI will be much shorter than a decade, there are some fundamental questions to be answered and much testing and evaluation will be required. Second, the JTWC forecast procedure is based on the (OTCM) (Appendix C). The ability to interpret the OTCM tracks in terms of the NVA is a key aspect in the JTWC forecast procedure. Thus, the NVA will continue to be generated at FNOC to support JTWC until an improved ATCM is adopted. Third, it is scientifically prudent to begin the ATCM development using the NVA until it can be demonstrated that a regional OI scheme provides similar or improved forecast accuracy.

The number of analysis levels in the NVA should be expanded to support a high vertical resolution model. The present NVA wind analysis levels are surface, 700, 400 and 250 mb (Appendix E). An 850 mb analysis would give greater weight to the low-level cloud-motion vectors than is currently possible. Furthermore, the low-level divergence field in the tropics would be better represented at 850 mb than at 700 mb. An analysis at 500 mb would also be desirable to better resolve the mid-tropospheric winds that are known to be important for tropical cyclone steering. Additional levels in the NVA wind fields would support research groups who have used the archived NVA fields (1973-present) to improve our understanding of tropical circulations (C.-P. Chang, personal communication). However, the viability of the OTCM must be sustained in support of JTWC forecasts before any significant changes are implemented at FNOC.

The objective analysis of humidity fields is a special problem. When an active latent heat parameterization scheme is introduced into the model component of the ATCM, there must be a specification of the initial relative humidity field. The Kuo-type parameterization schemes are very sensitive to the low-level humidity. Erroneous tropical cyclone track forecasts may result from the fictitious intensification (or decay) of the tropical cyclone or of adjacent synoptic circulations (Hacunda, 1978; Elsberry, 1979). Relative humidity analyses are not presently made for NOGAPS or NORAPS. Rather, the previous 12 h forecast of the humidity field is used as the initial condition. While this may provide a stable estimate that is internally consistent for large-scale models, erroneous features in the humidity field are also perpetuated. Methods to specify the initial humidity fields for the ATCM must be developed and tested.

C. Data-Checking Aspects

The importance of data-checking algorithms for improving numerical weather prediction has been given greater and more widespread recognition. Forecast evaluations at the European Center for Medium-range Weather Forecasts (ECMWF), Goddard Laboratory for Atmospheric Science (GLAS), NMC and elsewhere have demonstrated the need to improve the automated methods for rejecting/accepting observations. A. Pike (NHC) presented an example in which the insertion of a single rawinsonde report resulted in a dramatic and erroneous change in the forecast track from a barotropic model. Although the present NVA and the NOGAPS analysis systems delete observations which are judged to be erroneous, the data checking problem will very difficult near a tropical cyclone.

One desirable attribute of the OI scheme is that it provides a systematic basis on which to reject an observation. The global OI routine being developed by E. Barker of NEPRF will include a "buddy check" system patterned after that at ECMWF. It is clear that the horizontal structure functions of the OI have to account for the various scales of motion in the tropical cyclone, and will depend on how the storm circulation is specified. Because the OI will be three-dimensional, another critical question is the vertical structure of the weighting functions. Much testing will be required to implement these data-related routines.

The movement of the tropical cyclone is primarily determined by the large-scale advection of vorticity, although there are significant secondary circulation effects (Holland, 1983; Chan, 1982). Simple linear relationships based on these ideas may provide a quality control method for assessing the realism of the initial storm tracks from dynamical models as well as from the analyses. Stand-alone computer capability at Guam beginning in 1986 will provide the resources necessary for this quality control aspect.

The importance of quality control requires a "smart" analysis systems. A general program of this type is being started by S. Payne of NEPRF. It is recommended that a special working meeting be held at the appropriate time to address the specific data-checking and data-analysis routines required for the ATCM.

D. Analysis concepts

A conceptual view of the analysis system for the ATCM is shown in Fig. 1. The large-scale domain, with dimensions considerably larger than the domain of the numerical model in the ATCM, will be interpolated from the global analyses. These may be either the spherical NVA or the NOGAPS analyses. The issue on this scale is the realism of the large-scale circulations. At present, it appears that the NVA analysis is most appropriate for the tropics. It is expected that the NOGAPS analysis will be more competitive when the OI and nonlinear normal mode initialization updates are implemented. In particular, the "sloshing" in the tropical wind and pressure fields that may cause the rejection or inappropriate acceptance of observations, should be reduced and the analyses should more closely match the observations.

The environmental domain in Fig. 1 is loosely defined as the region of influence of the tropical cyclone during the 72 h forecast period. This domain is slightly larger than the horizontal dimensions of the numerical model in the ATCM to minimize boundary condition inconsistencies. Within the environmental domain, there will be a re-analysis that will incorporate all late observations received since the preliminary global analysis. This would include any synoptic system bogus data submitted to FNOC by the regional centers. Sandgathe (Appendix C) suggests that adjacent synoptic features, such as narrow ridges, TUTT lows, etc., may cause the track to deviate from the steering implied by the large-scale features resolved on the global domain. There is some concern whether these adjacent synoptic features will be adequately resolved in the available observations. Furthermore, it is not clear that the operational analysts can consistently represent these features and that the bogus data can be inserted so that the features are retained by the forecast model. At any rate, the purpose of the re-analysis on the environmental domain will be to use all possible data (including bogus soundings) to infer important synoptic-scale circulations.

We do not anticipate that there will ever be sufficient observations in the horizontal and vertical to resolve adequately the inner-core region of the tropical cyclone. An asymmetric distribution of observations may distort the analysis, especially in the nearly circular flow around the center. The consensus of the DAI group is that the inner core must be specified by a bogus storm. This "bogus" must take into account the horizontal scale of the actual

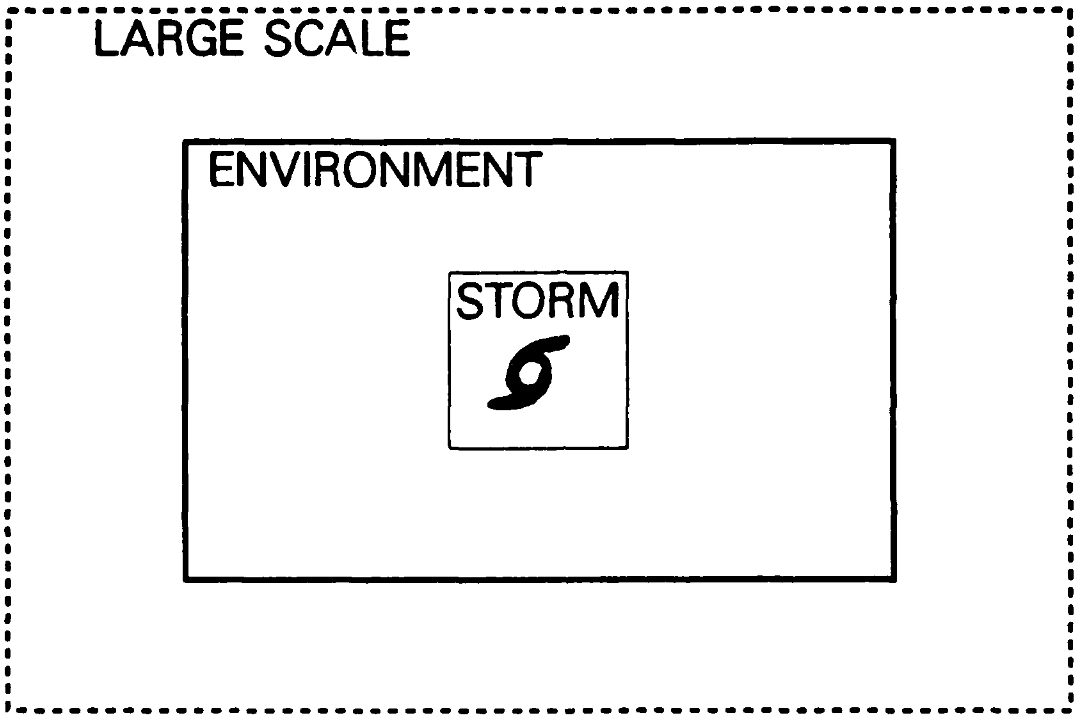

Fig. 1. Schematic illustration of the three domains of the analysis routine for the ATCM.

storm; that is, a different bogus is required for a storm with a 400 n mi radius of 30 kt winds than for a 100 n mi radius. Just as important, the depth of the bogus circulation must distinguish deep tropospheric cases from the shallow or "sheared-off" tropical cyclones.

The bogus storm should be selected by JTWC personnel from a menu of predetermined cases. Reconnaissance data will normally provide the necessary information to select the bogus, although provisions must be made to use satellite or conventional data when reconnaissance is unavailable. Investigations of past reconnaissance data by Gray's group at CSU should assist in the specification of these bogus storms. Gray's group has found that the strength (defined as the average wind speed between 60 and 150 n mi) is a relatively conservative parameter. As Sandgathe points out (Appendix C) the major concern of the JTWC customer is the maximum wind speed that will occur at the location. Thus, the correct specification and prediction of the wind distribution is an important goal.

The storm bogus that is inserted should be consistent with the dynamical model equations. Fiorino (Appendix F) will test a three-dimensional bogus storm circulation that is consistent with the specified heating function of the NTCM. Such a bogus storm will be better balanced, and it is hoped that much of the oscillatory motion along the track in the NTCM with the present a priori specification will be eliminated.

In summary, there are three scales in the analysis for the ATCM. The background large-scale circulation will be interpolated from a global analysis. A re-analysis on a finer grid will use all available observations with a later cutoff time. An appropriate storm bogus that is consistent with the model physics will be used to specify the inner-core circulation. Some interpolation may be necessary to provide the initial conditions on the model grid(s), especially if there is an inner nested grid with finer resolution than the analysis grid.

E. Analysis Procedures

The analysis aspects will be treated in two phases. The initial procedure will be based on the NVA, as indicated in Fig. 2a. The spherical NVA currently has a data cutoff of about +7 h after synoptic times. This analysis will be evaluated by the regional centers and the bogus reports will be transmitted to FNOC to specify poorly defined synoptic features adjacent to the tropical

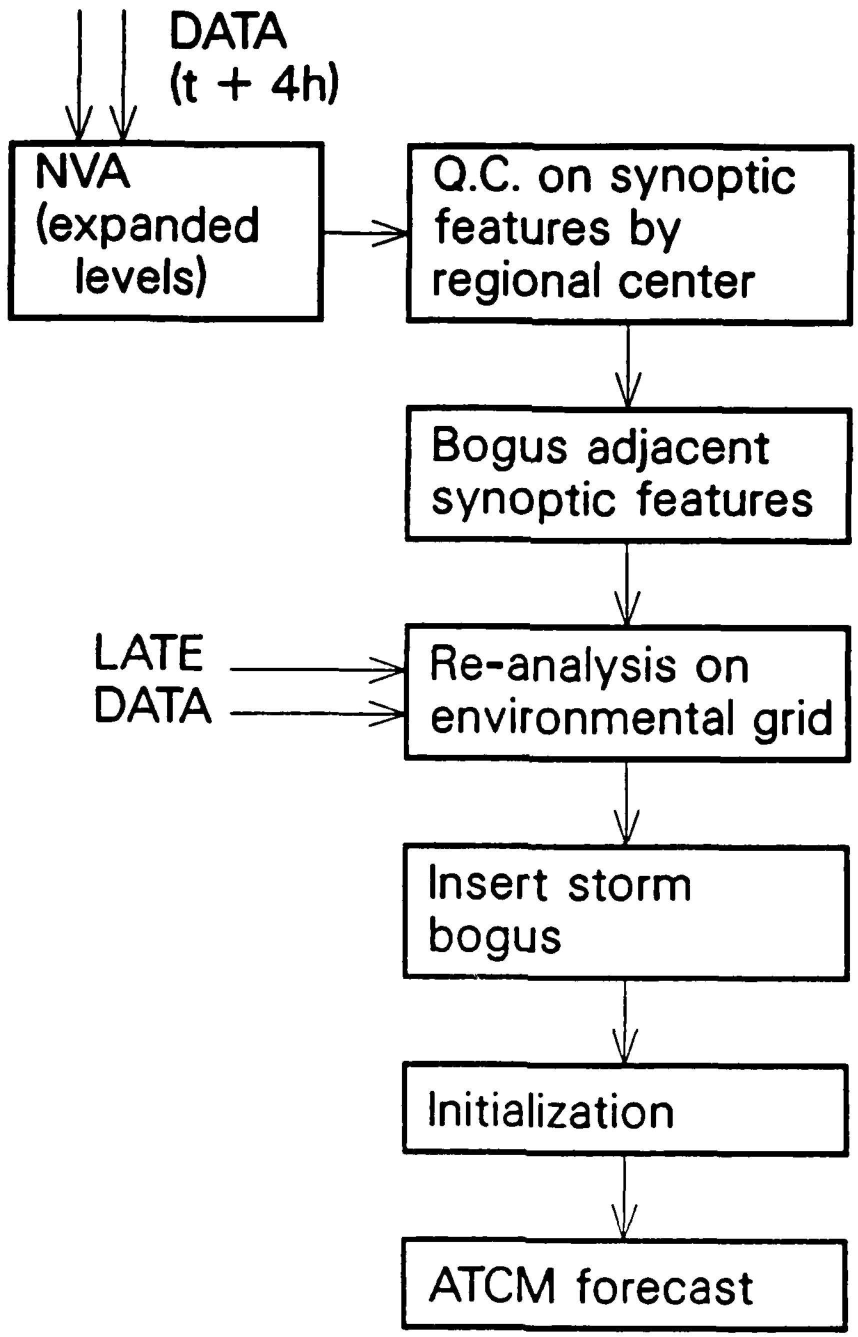

Fig. 2a. Flowchart of NVA-based analysis procedure for the ATCM.

cyclone. Using the larger data sample at a cutoff of about 8.5 hours, a re-analysis will then be made on the environmental grid (see Fig. 1). A storm bogus will be added to specify the inner-core circulation followed by the initialization and forecast phase. The cut-off time of the initial NVA may have to be adjusted by an hour or more for timeliness considerations.

A second analysis approach (see Fig. 2b) based on OI routines will be developed as resources become available. The first-guess field for the regional OI (environmental grid) will be the global OI fields. That is, the difference between the observation and the global OI value interpolated to that location will be analyzed and then added to the global analysis to form the regional analysis. The remainder of the steps are similar to Fig. 2a. However, two optional steps are indicated in the right column in Fig. 2b. If the bogus of the adjacent synoptic features leads to improved tropical cyclone forecasts, the bogus could also be used in the global re-analysis. The second option would be to use the previous 12 h forecast of the ATCM model as the first guess for a regional update. This procedure will first be tested for the NORAPS forecast region centered over the Mediterranean (R. Hodur, personal communication). The application would be more involved if the regional grid is relocated each 12 h following the tropical cyclone.

F. Pre-processing Considerations

A pre-forecast modification of the initial wind fields that adjusts the initial tropical cyclone forecast track toward observed motion has been shown to be effective at all time intervals for the predecessors of the OTCM, but only at 24 and 48 h for NTCM tests (Appendix F). An adjustment of the wind field to completely account for departures from a persistence of past motion track effectively assumes that all the early track forecast error is due to large-scale and storm-scale data errors. Model errors related to horizontal or vertical resolution, incomplete physics packages, etc., are also involved. Consequently, an overly aggressive technique of forcing persistence into the early portion of the dynamical model track may be detrimental, as the experiments of Fiorino imply. It has been generally observed that tropical cyclones frequently decelerate as they approach the recurvature point. Insertion of a persistence component may cause the dynamical model to overshoot the recurvature point (Appendix C). That is, recurvature is suggested by the shape of the forecast track, but the 72 h forecast location is too far to the west.

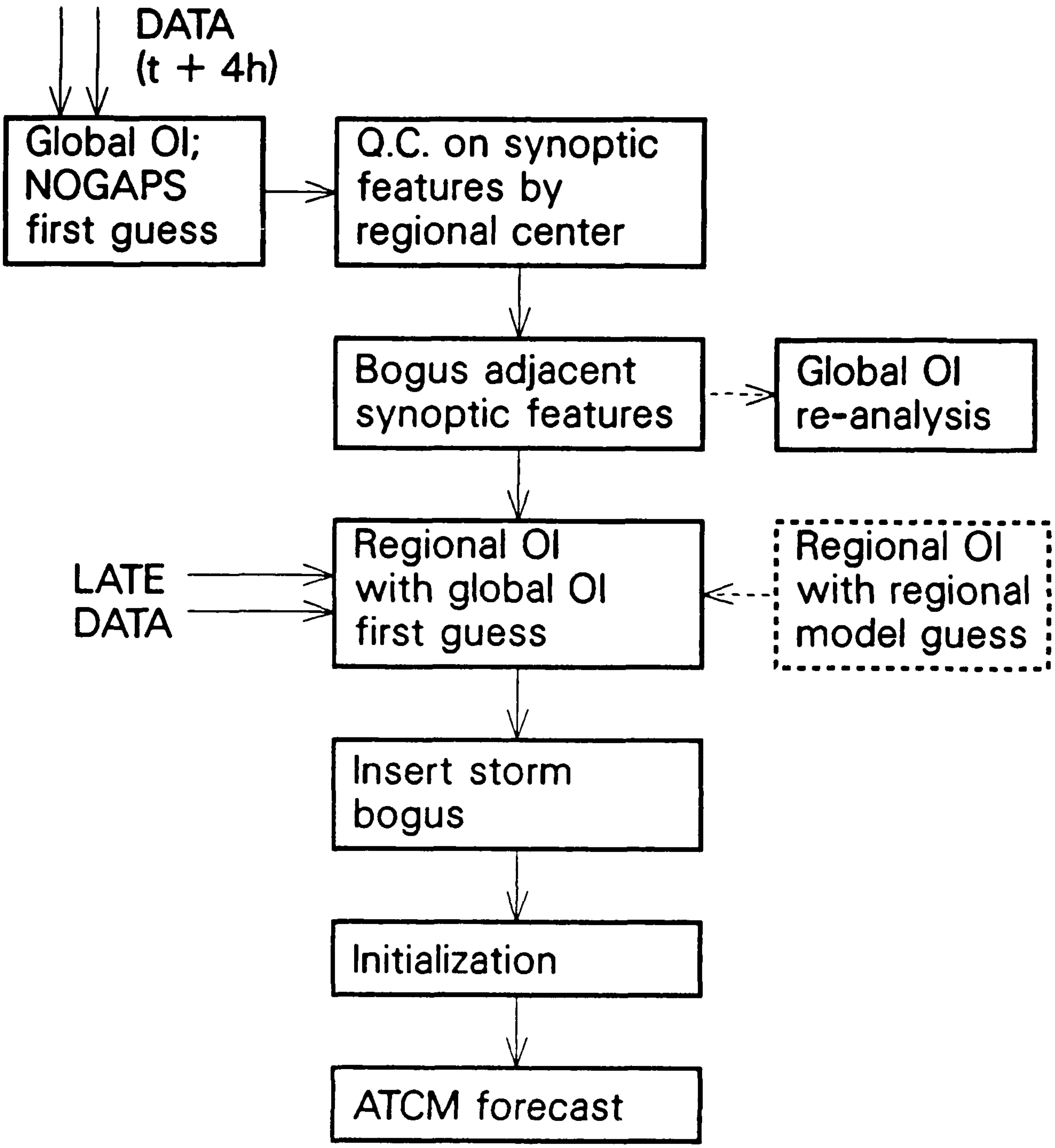

Fig. 2b. Flowchart of OI-based analysis procedure for ATCM.

Pre-processing is basically an empirical fix that accounts for poorly resolved large-scale and storm-scale fields and for model deficiencies. The new data analysis system, including a storm bogus that accounts for horizontal and vertical variations in storm circulation, should greatly reduce the need for pre-processing. Data assimilation techniques are available that allow for the insertion of a sequence of storm circulation features (e.g., dynamic initialization by nudging (Hoke and Anthes, 1977)). Similarly, the ATCM numerical model with proper horizontal and vertical resolution and improved physical representations should also reduce the need for pre-processing. Furthermore, the operational group requested that the raw model forecast track be transmitted. If it is necessary to add a pre-processing (or post-processing) option to the new model, it should be a switch option specified by the user.

In conclusion, a pre-processing component does not seem to be desirable a priori because the planned improvements in data analysis and in the numerical model should reduce the need for such empirical procedures.

G. Initialization

Nonlinear normal mode initialization (NNMI) techniques tend to remove the divergence in the tropical wind fields. This has led to several alternatives for specifying the divergent component, including diabatic initialization or inferences based on the outgoing long-wave radiation pattern (Julian, 1984). There are also difficulties in applying NNMI techniques to limited area models, although the Canadian and French groups have successfully used the initialized fields extracted from a high-resolution, global initialization. An alternative to NNMI for regional models has been suggested by Bourke and MacGregor (1983). Their vertical mode initialization (VMI) scheme does not involve the horizontal structure functions of the NNMI. Only the vertical normal modes are adjusted to produce a smooth evolution of the variables during the first 12 h of the forecast. Such an initialization routine is being prepared for NORAPS, and should be available for use in the ATCM. Although the initialization would not likely change the 72 h track forecasts (at least with non-interactive heating), it will be necessary to remove the spurious divergent components. If the oscillations of the pressure fields during the early forecasts are reduced by VMI, the short-term oscillations in the forecast track should also be reduced. Thus, the vertical mode initialization is a good candidate for initialization in the ATCM.

Dynamic initialization, which "nudges" the initial fields toward a sequence of observations during a pre-forecast period, is another alternative. This procedure has the advantage of creating internally consistent fields on the storm scale because of the strong heating associated with the storm. Although the model is being forced to an analysis, the lack of heating on larger scales may result in a less than accurate initial state. It seems appropriate now to postpone application of such dynamical initialization techniques for the ATCM.

H. Tentative Time Schedule

Sandgathe (Appendix C) has indicated that two dynamical model forecasts per day would be adequate, and that these model forecasts should not be based on analyses that were valid 18 h previously. Captain Nicholson (Appendix D) showed that the operational stream at FNOC would be heavily constrained during the NOGAPS time slot if a more sophisticated (time-consuming) tropical cyclone model other than the NTCM was proposed. The analysis times implied in Fig. 2 are designed in part to take advantage of computer resource availability after the completion of the NOGAPS integration. Moving the dynamical tropical cyclone model to a later slot will also allow manual intervention by the regional center. Further, more tropical observations will have arrived by the later data cutoff time as well as an additional fix at t+6 h. The bogus storm could be inserted at this location within the analyzed fields without degrading the forecast, based on the experiments with the NTCM. It is also anticipated that the analysis prepared in this time slot will lead to a more consistent storm track.

The ATCM will use time-dependent boundary conditions which can be obtained from the just completed NOGAPS prediction if the later time slot is adopted. Sandgathe (Appendix C) indicated that the warning schedule could be adjusted to accommodate a later arrival time for the dynamical guidance. The period allotted for feedback from the regional center in Fig. 2 is consistent with the period of hand analysis at JTWC. Thus, an ATCM run at about t+8 to t+9 h should make optimum use of the available data, satisfy computer constraints, and still meet the JTWC forecast schedule.

4. Numerical Issues

A. Domain and Resolution Considerations

Given finite computer resources, there must be a trade-off between the horizontal and vertical resolution in the model and the domain size. The physical factors to be considered include: (i) the scales of latent heat release, e.g., eyewall diameter, rainbands; (ii) vortex-basic current interaction; (iii) multiple tropical cyclone interactions; and (iv) tropical cyclone interactions with adjacent synoptic features.

(i) Representation of the latent heat release processes on the scale of individual cumulus clouds or groups of cloulds will require a minimum resolution of 5-10 km. A triply nested grid model with inner grid resolution on this order has been integrated by R. Jones of the HRD (NOAA). His model is extremely expensive model to run. Furthermore, it is not clear to what extent the inner storm processes (as represented in such a model) affect the track. Given present computer resources and other areas of more promise for improving track prediction, it would be inappropriate to consider a nested grid capable of resolving the eyewall scales at this time.

(ii) The primary interaction of the storm vortex with the basic current probably occurs on a horizontal scale of the order 300 to 700 km. The higher resolution operational dynamical tropical cyclone models have a grid spacing of 40-60 km (Elsberry, 1983). It is uncertain how much improvement in track prediction would be possible from a 25-30 km resolution, especially if no attempt is made to realistically treat the eyewall processes. It is therefore recommended that the first version of the ATCM model have a horizontal resolution of about 50 km, and a vertical resolution of about 10 layers within the troposphere.

(iii) The operational group requirement that has the largest impact on the design of the ATCM model is that multiple tropical cyclones must be resolved. The domain of existing dynamical models was established by the horizontal scale of the tropical cyclone and (especially) the horizontal distance that the cyclone might travel in 72 h. An appropriate domain size for the single storm situation is 7000 km (east-west) by 5000 (north-south) km. The problem becomes more complex when two cyclones are involved. An alternative of having separate nested grids centered on each storm was considered and rejected because of the complex coding that would be required. The only alternative is to have both

storms resolved uniformly on the same grid. If the storms are not to be within 1000 km of the boundaries at the end of the forecast, an appropriate domain size is 9000 km by 6400 km for the multiple storm situation.

(iv) The operational group requirement group that the ATCM predict the impact of adjacent synoptic features on the tropical cyclone track is also important. Given the horizontal resolution considerations in (ii) and (iii) above, these features should be adequately resolved (in a predictive sense, if not in an observational sense) by the uniform grid resolution over the domains above.

Contrary to the pre-planning meeting "strawman" proposal (Appendix G), it was recommended that the first version of the ATCM model have a uniform horizontal grid rather than a nested grid. When the NTCM was developed in the 1970's, nesting was the only economically feasible method to obtain improved resolution near the tropical cyclone. It is now possible to resolve large domains with a resolution of 50 km without nested grids. A nested grid model should be considered only if it can be demonstrated by future research that the nesting actually improves track prediction relative to the uniform grid. A uniform grid version of the nested NORAPS model being developed for midlatitude prediction would be appropriate for these tests.

The requirement for such large domains is the necessity of placing the boundary zone as far away as possible from the inner region of prime interest. The numerical group suggested that about 15% of the track errors in present dynamical models is associated with the boundary conditions. The contribution of errors and the information from the boundary values is reduced as the domain size is increased. The dynamical/physical processes of the ATCM must properly treat all the tropical and extratropical systems throughout the domain if negative boundary impacts are to minimized. Time-dependent boundary conditions around the perimeter are the best approach. The most recent forecast from the NOGAPS should be used to specify the boundary conditions of the ATCM model.

A related problem is the strategy for adjusting the internal solution to the externally-forced boundary values. A typical approach (after Perkey and Kreitzberg, 1976) is to "buffer" the model solution with a linear weighting of the internal and external solutions in the boundary zone. A heavy smoother is generally required in the buffer zone to eliminate the inevitable noise

generated by this approach. Because there is no completely satisfactory strategy, further research will be necessary to derive suitable lateral boundary conditions.

B. Numerical Aspects

In the strawman proposal (Appendix G), it was suggested that a traditional finite difference model (NORAPS) be adopted as the dynamical framework for the ATCM. The judgment of the numerical group was that about 10% of the track error in present models is due to truncation errors (horizontal, vertical and temporal). The NORAPS model has fourth-order accuracy and a highly efficient split explicit time differencing. The staggered (Scheme C) grid and "sigma" coordinate system are desirable features of NORAPS compared to the non-staggered grid and pressure coordinates in the present Navy dynamical tropical cyclone models. It is recommended that the NORAPS be adopted as the dynamical framework for the ATCM rather than pursuing an extensive intercomparison of recently developed research models.

C. Physical Processes Considerations

An essential consideration in the design of the ATCM is the requirement for predictions of the interaction of the tropical cyclone with the basic current and adjacent synoptic features. It follows that the physical package of the ATCM must be capable of representing the energetics of each of these phenomena. The numerical group estimated that about 20% of the present track errors may be attributed to an improper representation of these physical aspects. It is clear that a 50-km grid spacing is too coarse to simulate the eyewall processes in the tropical cyclone. Thus, the goal in this resolution is to represent the vortex scale features. Prediction of the basic current changes in the tropical region requires an adequate treatment of land and sea, large-scale heating in cloudy regions versus non-cloudy regions, nonlinear energy exchanges, etc. The required physical processes for predicting adjacent synoptic features is somewhat uncertain at this time. The few attempts to predict these tropical circulations suggest that a rather complete physical package is required. Clearly, the most important physical process is the release of latent heat and its link to the planetary boundary layer. Radiative effects may also be important in some synoptic-scale systems (such as TUTT lows) and over land.

The present Navy dynamical tropical cyclone models have a fixed analytical representation of the latent heat release only within the tropical cyclone. A moisture analysis and prediction is thereby avoided. However, this simple heating distribution does not presently represent the multitude of horizontal, vertical and temporal variations actually occurring in tropical cyclones. Furthermore, the adjacent synoptic features may not be predicted well with an adiabatic model (Appendix F).

There are many potential sources of error associated with any interactive latent heat release scheme. In many cases, these errors may be traced to an erroneous initial moisture distribution. The philosophy behind the NTCM is that is better to keep the model simple rather than introduce additional degrees of freedom. The speed bias in the NTCM may be related to the assumed and fixed relationshop between heating and the storm center. Whereas the heating function in the OTCM is centered at the location of minimum 1000-mb height from next time step, the heating in the NTCM is placed on the current center of maximum lower tropospheric vorticity. While the non-interactive heating distribution is useful as an initial step, further progress will require inclusion of a sophisticated physical package. In recognition of the potential hazards of introducing an interactive physics package, it is desirable that "bounds" be placed on the magnitudes of the latent heat release to prevent uncontrolled changes.

It is recognized that the physics package requires a significant fraction of the computer resources. According to R. Hodur, about 30% of the integration of NORAPS is consumed in the physics package. Nearly 95% of that time is associated with radiation calculations. As a first-order estimate, a similar time allocation between physics and dynamics was recommended for the ATCM model.

One of the primary problems associated with interactive heating techniques is the specification of the initial conditions. Research is required on several aspects including: 1) a specified heating distribution as part of the initial storm bogus; and 2) a dynamical initialization technique in which a realistic heating distribution is generated for the initial vortex representation on a 50 km grid.

Two approaches are possible for the planetary boundary layer parameterization. The more simple approach is to use a bulk version with a prediction equation for the depth of the layer. The alternative is to add predictive levels within the planetary boundary layer to calculate explicitly the vertical structure and fluxes. Additional research is required prior to selection of a bulk or multi-level representation of the planetary boundary layer in the ATCM model.

D. Topography Considerations

One of the lower priority requirements levied by the operational group was improved prediction of the effects of topography on the tropical cyclone (Appendix C). Research studies on this topic have been carried out at NRL and the Geophysical Fluid Dynamics Laboratory (GFDL). It is recognized that a 50-km grid cannot resolve smaller scale features in the topography. The consensus is that inclusion of topography in the ATCM will not be a problem because the NORAPS system already accounts for orographic effects.

E. Sensitivity Tests

Design of such a complex system as the proposed ATCM requires provision for sensitivity testing of the separate components. These tests may consume considerable time and resources. Thus, it will be essential to learn as much as possible from sensitivity experiments being done at NCAR, GFDL and NRL. Some testing, however, must be done with the ATCM. The highest priorities should be on the effects of: (i) structure of the bogus storm; (ii) planetary boundary layer representations; (iii) horizontal resolution; and (iv) relative humidity specification. The general approach is similar to observing systems sensitivity experiments. Predicted fields from the most complete and sophisticated model possible with present computer resources are the control. A degraded version of the model or of the "data" is used to determine the departures from the control. One of the advantages of these tests is that some estimates can be made as to the most important factors limiting the tropical cyclone track predictions. These estimates may vary between tropical cyclone basins and may be seasonally dependent.

F. Model Outputs

The ATCM should provide: 1) predictions of positions, intensity, wind distribution; and (2) initial wind fields. The storm center in a dynamical model can be located in several ways. The overall vortex should be tracked rather than a small-scale feature (such as minimum pressure) which may include short-term fluctuations. The current data base, existing knowledge of the tropical cyclone dynamics and the accuracy of physics parameterizations do not allow intensity forecasts to be made by a dynamical model. However, it does appear to be feasible to estimate the radius of 30 and 50 kt winds at 24 h and the radius of 30 kt winds at 48 and 72 h. Some statistical processing of the model variables may be required to achieve acceptable accuracies. The initial wind fields are necessary for the forecaster to interpret the predicted storm track. Transmission of all of the 10 or more levels will not be necessary. Experimentation will be necessary to select the most appropriate levels.

The operational group requested that the unmodified, or "raw," track predictions be provided for direct comparison with the initial wind fields. The planned improvements in data analysis and in the numerical model should reduce the systematic biases in the tracks. The necessity of post-processing (statistical adjustment to reduce systematic track errors) will be determined at a later time.

There is presently no operational requirement to archive the fields used in the ATCM. However, archiving is essential during the research and development phase. Demonstration of model improvements is only possible if the same cases can be repeated. Thus, the initial fields and storm-related inputs must be archived for a representative sample of cases. The output variables should be archived for forecast evaluation purposes. Research is in progress to alert the forecaster of the storm situations, or other conditions, when the dynamical model is likely to produce good or bad forecasts. Evaluation of the ATCM will require a large sample of cases for development and testing purposes.

Recall that the stated operational requirement was to provide forecast guidance to the forecaster. It has now been accepted by JTWC that dynamical models can provide 48 and 72 h forecasts of comparable accuracy to the official forecasts. It is no longer necessary to run large numbers of cases just to demonstrate the viability of the dynamical model. Rather, the focus has shifted

to using the dynamical model to treat those difficult cases for which other objective aids are incapable of producing accurate forecasts. Sandgathe (Appendix C) summarizes these situations. Consequently, the validation process can now focus more on the understanding of the model performance in these difficult cases. The OP group suggested that about 30 "classic" storms and 30 "high-interest" storms be selected from two or three different seasons to form the validation sample. The research version of the dynamical model must produce consistently superior forecasts compared to the OTCM. Then, it must perform well during an operational evaluation with a significant sample of storms. The goal of the dynamical model development will only be achieved when JTWC can use it operationally to improve tropical cyclone prediction.

5. Research Plan Framework

We now summarize the discussions of the relative priorities of different aspects of the ATCM dynamical tropical cyclone forecast system. The goal of this section is to provide a framework based on scientific reasoning at the present time. A detailed research plan will have to be developed internally at NEPRF and will strongly depend on available personnel, computer resources and other considerations. Of course, this plan will continue to evolve as the development progresses.

The strawman proposal (Appendix G) prepared before the meeting was considerably revised (Table 1). The first step is to test the numerical aspects of the NORAPS in a configuration similar to NTCM to determine if the significant slow bias in the NTCM storm tracks is reduced. A uniform grid version with about the same horizontal resolution as the NTCM will be used, however, the domain with high resolution can be much larger. About 25 cases that had a slow bias and 25 cases without a bias will be tested. In a series of sensitivity tests, vertical and horizontal resolution will be varied to determine optimum configurations (1.1). One of the major departures from the strawman is that an early test of the impact of physical processes is suggested. A Kuo-type latent heating parameterization and a planetary boundary layer would be introduced at this stage (1.2). These physics packages are presently available as part of NORAPS, so the major effort would be to test their applicability to the tropical cyclone situation. A relative humidity distribution is also required when the dynamical model includes moist processes.

Table 1. Proposed research plan for developing and testing various components of the Advanced Tropical Cyclone Model.

Version	
1.0	Configuration similar to 1984 version of the Nested Tropical Cyclone Model* to determine the contribution of numerical aspects to the slow track bias.
1.1	Sensitivity to vertical and horizontal resolution.
1.2	Introduce latent heating parameterization (Kuo) and planetary boundary layer.
2.0	Improved storm bogus within inner grid that has realistic horizontal and vertical structure.
2.1	Regional objective analysis of winds (optimum interpolation).
2.2	Initialization (nonlinear vertical mode).
2.3	Regional objective analysis of relative humidity.
3.0	Test storm-scale bogus and insertion of adjacent synoptic features.
3.1	Test improved planetary boundary layer representations.
3.2	Test other latent heating parameterizations.
4.0	Triply-nested version, testing the effect of horizontal resolution (possibly 25, 75 and 225 km grids).
5.0	Model intercomparisons.

*NTCM 2.0 characteristics: fine-mesh grids, 41 km; coarse-mesh grid, 205 km; three pressure layers of 300 mb depth; analytic heating pattern following storm center; no moisture fields; no planetary boundary layer; channel boundary conditions on coarse grid; simple storm bogus within entire fine grid.

The second phase of the development is related to data aspects. First, a specification of the initial structure of the tropical cyclone is required (2.0). A realistic wind distribution in the horizontal and vertical is essential, as well as the thermodynamic fields to properly drive the explicit physics parameterization. A two-stage analysis procedure is suggested. The NVA procedure can be immediately adapted for the regional re-analysis. Meanwhile, the development of a regional optimum interpolation (OI) can proceed as a parallel effort (2.1). It is also appropriate to introduce the vertical mode initialization at this stage to reduce the amplitude of the gravity modes in the initial conditions (2.2). During stage (1.2), the humidity distribution in the large scale can be derived from a prior large-scale forecast. This task is put near the end of this stage in recognition of the amount of time and research that may be necessary to accomplish the task and because a NOGAPS moisture analysis will be developed in the next 2-3 years.

In the third stage, the impact of improved specifications of the storm-scale and adjacent synoptic features will be assessed. A variety of complete bogus storm specifications that are appropriate to each situation will be tested (3.0). Concurrent dynamical model testing might include improved formulations of the planetary boundary layer (3.1). It is hoped that a complete physics package would allow adequate predictions of the adjacent synoptic features as well as the tropical cyclone vortex. Tests with other latent heating parameterizations may be required at this stage (3.2). The fall-back position is the specified heating distributions in the horizontal and vertical and in time.

A second major departure from the strawman proposal was to suggest the delay of a nested grid version until stage (4.0). Development of a triply nested version was viewed to be a high risk venture compared to likely benefits. Rather than devote a significant effort to this task in the early stages, it was suggested that work begin immediately on the high-resolution uniform grid model which should be adequate for the purpose.

The final stage (5.0) calls for model intercomparisons. A series of case studies will be developed during stage (1.2) that can be shared with other research groups. The objective is to understand the basic physics of the tropical cyclone track problem by comparing with different models. This stage should lead to a specification of future model requirements.

6. Conclusions

The attendance of representatives and researchers from most of the U.S. agencies involved in tropical cyclone prediction is an indication of the interest in this important topic. A willingness by these experts to share experiences and offer advice contributed greatly to the success of the meeting. This type of interaction will facilitate future collaborative efforts on tropical cyclone prediction. Preparation and distribution of the position papers and issues prior to the meeting allowed more time for discussion of issues. It is significant that a strong consensus was achieved on many issues related to the numerical model. Although agreement was achieved on the importance of the data-checking and analysis aspects, the best solutions to these problems in the tropics are unclear at this time. However, a consensus was reached on what problems are likely to be encountered and on a general approach. Participation by the operational experts led to recommendations which are likely to be successfully implemented and which will address the most important operational requirements.

The research strategy adopted at the meeting should not be considered as fixed. Wider input is being sought through presentations at three meetings in early 1985: Interdepartmental Hurricane Conference; Pacific Typhoon Conference; and 16th Technical Conference on Hurricanes and Tropical Meteorology. The goals of the planning meeting will have been accomplished if this document provides a basis for an evolving, scientifically based research plan for developing an Advanced Tropical Cyclone Model.

7. Acknowledgments

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CAPT H. Nicholson, USN, C. Mauck and other FNOC staff also provided operational insights. Although all participants contributed, special thanks are given to R. Anthes, J. Lewis, CAPT J. Tupaz, USN, LCDR S. Sandgathe, USN, J.C.L. Chan, and J. Peak who served as group leaders and rapporteurs. Some of the typing of pre-meeting documents was done by L. Elsberry and by P. Jones (NPS). The assistance of NEPRF colleagues in preparing for the meeting is gratefully acknowledged. Preparation of this report was facilitated by Ms. Winona Carlisle and Mr. Steve Bishop of NEPRF.

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APPENDIX A

LIST OF PARTICIPANTS IN THE PLANNING MEETING ON DYNAMIC TROPICAL CYCLONE FORECAST MODELS 3-4 JANUARY 1985, MONTEREY, CALIFORNIA

(Sponsored by the Naval Environmental Prediction Research Facility)

Chairpersons: Professor Russ Elsberry, Department of Meteorology, Naval Postgraduate School

Mr. Mike Fiorino, Numerical Modeling Department
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CAPT Harry E. Nicholson, USN
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Fleet Numerical Oceanography Center

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*PCO as of 3-4 Jan 1985. Assumed command of NEPRF on 22 Jan 1985.

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APPENDIX B

SCHEDULE FOR THE PLANNING MEETING ON DYNAMIC TROPICAL CYCLONE MODELS

January 3, 1985

Time	Group	Room	Topic
0830	ALL	Ro-228	Welcoming remarks by CAPT Ken Van Sickle, USN, Commanding Officer, NEPRF
0845			Introductory remarks by Russ Elsberry on: - Goals of the meeting - Description of the schedule - Organizational aspects - Administration
0900			Operational considerations, LCDR Scott Sandgathe, USN, Deputy Director, JTWC
0940			Computer resources at FNOC, CAPT Harry Nicholson, USN, Commanding Officer, FNOC
0950			Considerations for running an ATCM operationally at FNOC, Charlie Mauck, FNOC
1000			**BREAK**
1015	ALL	Ro-228	NTCM Development, Mike Fiorino, NEPRF
1045			Short Presentations by: - Simon Chang, NRL - Arthur Pike, NHC - Mukut Mathur, NMC - Bill Gray, CSU
1200			**LUNCH**
1300	ALL	Ro-228	Summary of morning session, plans for the afternoon, and a brief review of the strawman for the ATCM, Russ Elsberry

1315	NUM DAI OP	Ro-228 Ro-200C Ro-236	<u>GROUP DISCUSSION SESSION 1</u> - Discussion of broad issues. The OP group will revise the pre-meeting operational requirements document.
1445	ALL	Ro-228	Feedback from the OP group, CAPT Tupaz, USN, Deputy CNOC
1515			**BREAK**
1530	NUM DAI	Ro-228 Ro-200C	<u>GROUP DISCUSSION SESSION 2</u> - The OP group will join NUM and DAI to discuss narrowed issues and develop a preliminary priority lists.
1700			**ADJOURN FOR THE DAY**

January 4, 1985

0830	ALL	Ro-228	Review of the preliminary priority lists by group chairman. Coordination on overlapping issues.
0900	NUM DAI	Ro-228 Ro-200C	GROUP DISCUSSION SESSION 3 (Part 1) - Finalization of priority lists. Development of ATCM Research Plan. OP will join the NUM and DAI groups.
1130			**LUNCH**
1230	NUM DAI	Ro-228 Ro-200C	GROUP DISCUSSION SESSION 3 (Part 2) - Complete research plan.
1400	ALL	Ro-228	Final discussion of the research plans, wrap up of the meeting -- unresolved issues, follow-up and future coordination.
1530			Concluding remarks by CDR Don Hinsman, USN, Executive Officer, NEPRF

Notes - NUM is the Numerical Aspects Group, DAI is the Data Analysis and Initialization Group and OP is the Operational Group. Ro stands for Root Hall. The speakers at the short presentations will be given 15 minutes for their talk.

APPENDIX C

OPERATIONAL CONSIDERATIONS FOR THE DESIGN OF AN ADVANCED TROPICAL CYCLONE MODEL

From: LCDR S. A. Sandgathe
To: Planning Meeting for the Advanced Tropical Cyclone Model (ATCM)

Subj: OPERATIONAL CONSIDERATIONS FOR THE DESIGN OF THE ATCM

Encl: (1) Point Paper on Operational Considerations for the Design of the ATCM
(2) EG USPACOM Tropical Cyclone Research Objectives
(3) Joint Typhoon Warning Center Evaluation of the Nested Tropical Cyclone Model (NTCM)

Enclosure (1) is a point paper developed during a pre-planning meeting at the Naval Postgraduate School in November. Its purpose is to familiarize participants with the forecast problem from the Joint Typhoon Warning Center's point of view and serve as a starting point for discussions on operational requirements and constraints on the ATCM. The final statement of operational requirements will be developed by the workshop participants.

The Environmental Group of the Pacific Command (EG USPACOM) , an environmental advisory group which supports the Commander in Chief of all U.S. forces in the Pacific and Indian Ocean, has submitted a list of tropical cyclone research objectives (enclosure 2). This list is intended to establish priorities and give general guidance on areas where tropical cyclone research is required. The ATCM should not be designed with the expectation of solving or attempting to solve all aspects of tropical cyclone prediction. Emphasis should be placed on those aspects of the US EGPACOM requirements most suited to dynamical model solution and most likely to improve support to the operational community.

Scott A. Sandgathe
LCDR, USN
Deputy Director, Joint Typhoon Warning Center

Enclosure

Operational Considerations for the Design of an
Advanced Tropical Cyclone Model
(Prepared by LCDR Scott A. Sandgathe
for the
Planning Meeting on Dynamical Tropical Cyclone Models
Monterey, CA 3-4 Jan 1985)

I. The Warning Service

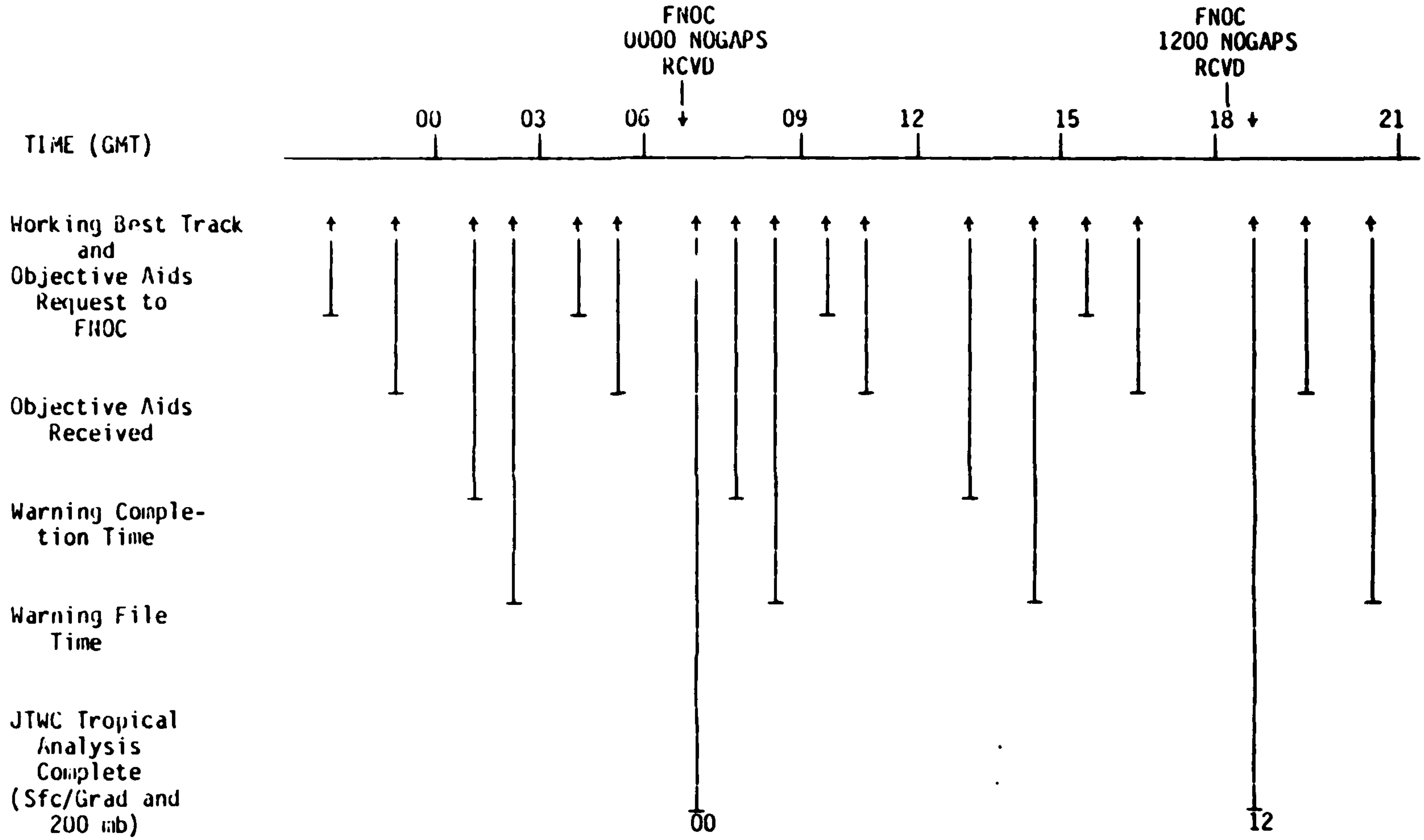
The Joint Typhoon Warning Center's (JTWC) area of responsibility (AOR) extends from the International Dateline to the east coast of Africa, which encompasses several climatologically different tropical cyclone regions. For tropical cyclones within this AOR, JTWC issues forecasts of track, speed, maximum intensity, maximum gusts and distribution of 30, 50 and 100 kt sustained winds. These warnings are issued by military message, AWN (automated weather network) bulletin, facsimilie broadcast, Coast Guard radio broadcast and telephone to DOD (all uniformed services) and State Department customers and to the civilian population within the Federated States of Micronesia and Guam. Forecast difficulty, DOD interest and data availability vary dramatically from region to region. For Northern Hemisphere tropical cyclones, JTWC issues forecasts each six hours valid to 72 hours. On Southern Hemisphere cyclones JTWC issues forecasts each 12 hours valid to 48 hours. Accurate 48-hour forecasts are normally adequate for air and naval bases in a single cyclone situation where adequate evasion opportunities exist. For ship routing and major operational exercises, 72 to 96-hour forecasts are required. During multiple cyclone situations 72 to 96-hour forecasts are required for evacuation of assets due to the sparcity of alternate bases in the AOR. This is to avoid costly multiple evacuations of aircraft or overloading of strategic bases. Accurate forecasts beyond 96 hours would result in little additional savings until they exceed seven to ten days and included genesis of systems.

II. The Forecast Procedure

JTWC warnings are currently issued with a file time of three hours after synoptic time (00, 06, 12 and 1800 GMT). The warning cycle commences three hours prior to synoptic time and completes with the transmission of the warning approximately two and one-half hours after synoptic time. Figure 1 highlights the key features of the JTWC warning cycle.

a. Updating the "working best track" is the first stage in the warning cycle. Fix information received up to three hours after synoptic time is used to interpolate an updated position at the previous synoptic time. The previous 48 hours of the cyclone track are also updated as required to provide a smooth representation of the cyclone movement. This "working best track" along with some basic synoptic information and storm characteristics is submitted via a computer link to FNOC. This information initiates a suite of climatological and dynamical objective forecasts aids. These aids generate forecast tracks and intensities based on the previous synoptic time (six hours before the current warning time). The dynamical aids are based on the most recent analysis (four to ten hours prior to warning time) and the NOGAPS forecast fields (six to eighteen hours prior to warning time). This objective guidance is generally received at JTWC one hour prior to warning time. All objective guidance, currently five climatological and dynamical aids, is plotted along with the previous official forecast for use in preparation of the warning.

JTWC Approximate Operational Schedule*



* Northern Hemisphere Schedule. JTWC issues warnings at 00 and 12 GMT or 06 and 18 GMT on Southern Hemisphere systems. Normally times (00/12 or 06/18) are staggered to distribute the workload in multiple cyclone situations.

Figure 1.

b. The warning position is developed from all fix information available up to one and one-half hours after warning time. This warning position is a blend of the expected position and the fix position. Fix position accuracies vary from over 60 n.mi. to less than 10 n.mi. depending on the fix platform and the stage of cyclone development. The average fix accuracy (departure from the fina best track") in the Northwest Pacific is 21 n.mi. with larger uncertai.. es and more variability in other regions of the AOR. Because of this uncertainty and the unrepresentativeness of the "fix" center to the center of the large-scale pressure disturbance, JTWC blends the fix position with the previous six hour forecast position in most cases. This procedure provides a more consistent and representative movement to the users.

c. The forecast track is completed one to two hours after warning time depending on the availability of the latest fix information. The primary guidance for the forecast track is generally the One-way Influence Tropical Cyclone Model (OTCM). The OTCM has demonstrated consistent skill over the past five years in identifying significant track and speed changes up to 72 hours in advance. The initial forecast on a developing cyclone will consist of a blend of persistence and the OTCM. Subsequent forecasts utilize the OTCM guidance and the bias OTCM has demonstrated up to the time of the forecast on that particular tropical cyclone. The forecast is modified in certain forecast scenarios based on other objective techniques and known model weaknesses. Two examples of modifications to the OTCM guidance include an adjustment for the known slow-speed bias of the OTCM on post-recurvature tropical cyclones, and anticipating more rapid response to mid-latitude systems than predicted by OTCM during recurvature situations.

d. Forecast intensities are developed from synoptic reasoning and climatology. Dvorak intensity analyses and 24 hour forecasts are blended with climatological intensities and the forecasters' best guess of the synoptic and topographical influences. Although a crude method, average intensity errors are small (20 kts at 72 hours) and generally have minimal impact when compared to track errors. Similarly, JTWC wind radii forecasts are based on climatological profiles, persistence of observed characteristics and synoptic reasoning.

III. Data Availability

Data availability and reliability varies dramatically across JTWC's AOR. In the Indian Ocean, conventional synoptic data are virtually non-existent and satellite imagery is only available as a low-resolution image relayed from FNOC. Satellite positioning and intensity estimates are obtained from indirect readout of DMSP satellite imagery at the AFGWC.

Aircraft reconnaissance is only provided for the Northwest Pacific tropical cyclones and availablilty is limited. Specification of the cyclone vortex characteristics is generally accomplished one to two times per day. Aircraft missions to specify the synoptic-scale flow are flown infrequently.

Even in the relatively data-rich Northwest Pacific, approximately one dozen upper-air stations report over an area larger than the continental United States. Most of these stations only report once each 24 hours and radiosonde data receipt has become intermittent since the recent change in political status in Micronesia.

DMSP and NOAA polar orbiting satellites provide excellent imagery over the Northwest Pacific. Geostationary satellite imagery is available on a three hourly basis and satellite-derived winds are generally available twice daily. The primary data sources (and the only one besides weather aircraft under U.S. control) within JTWC's AOR are the polar-orbiting satellites. JTWC relies heavily on satellite imagery to prepare accurate hand analyses. An objective analysis scheme to support the ATCM would probably also rely heavily on the indirect readout of data collected by these satellites.

<u>ATCM Goals</u> (by priority)

Goal 1: The primary goal of the ATCM must be to provide <u>forecast guidance</u> which results in consistent and correct track forecasts at 48 and 72 hours.

Background: Ideally, a dynamical model should make a perfect 72-hour track prediction. Failing this, the objective of the model should be to predict certain key forecast parameters. A model which accurately predicts changes in speed or direction can be manually combined with other guidance such as persistence or climatology to create an accurate track prediction. A model which can successfully predict (directly or indirectly) a period of quasi-stationary or erratic motion provides useful information to the forecaster even though the model track prediction may be incorrect.

The emphasis should be on forecast content in the model output, not on the least statistical error (RMS, mean vector, or right angle). Many (but not all) pre-and post-processing schemes actually mask useful forecast information available from the dynamical model. A model heavily biased toward persistence may continually fail to predict short-term track changes even though this is a crucial forecast paramenter. Yet statistics clearly show a model biased toward persistence actually has lower mean vector errors.

Goal 2: The ATCM should allow specification of the intensity, size and stage of development of the initial storm vortex.

Background: The movement of a tropical cyclone is highly dependent on its horizontal and vertical structure. A very large system can interact with synoptic-scale features up to 1000 n. mi. away. A very small system may have its entire circulation contained within a 100 n. mi. radius. The movement of these two systems will be quite different under identical synoptic situations. Therefore accurate dynamical model track prediction requires an accurate specification of the vortex dimensions. Ideally this should be an integral part of the data analysis and initialization portion of the system. If this is not possible, provision should be made to insert a bogus storm as specified by JTWC.

The stage of tropical cyclone development is also critical to the track. A developing or mature cyclone will be steered by the vertically-integrated flow in the region. A weakening or shallow system which has lost its vertical structure will be guided by only the low-level flow. Thus, a specification of vertical extent would be beneficial.

Additionally, it will be necessary to allow the storm structure to change over the period of a 72-hour forecast. If the ATCM does not reliably predict such structure changes, there should be a provision for JTWC to specify an anticipated change.

Goal 3: The ATCM should be able to handle multiple storm interaction.

Background: JTWC issues warnings on multiple cyclones in the Northwest Pacific approximately 60 days of each season. As many as five tropical cyclones have existed simultaneously in the region, and adjacent cyclones frequently influence each others track. During the 1984 cyclone season, there were five cases in which the interaction of two cyclones resulted in large forecast errors.

When two cyclones interact, there are several potential forecast scenarios. The forecaster is generally ill-equipped to solve this complex interaction problem. Currently, all of the JTWC's forecast aids (including the dynamical models) assume the presence of a single tropical cyclone. The multiple storm interaction problem appears to be particularly well suited for solution with a dynamical model. To adequately model this interaction, the size, intensity and future development of the two systems must be accurately modeled as the resultant motion often appears to evolve from generally small imbalances between the two vortices.

Goal 4: The dynamical model output should result in accurate predictions of maximum intensity and wind distribution. If this is not possible, it should adequately predict the size and asymmetries of the destructive wind envelope.

Background: Operational decisions in JTWC's AOR are based primarily on the distribution of damaging winds (generally 30 kt for ships at sea and 50 kt for shore installations). Although present track errors are generally greater than wind envelope errors, both must be reduced to meet the needs of the operational customer. Interaction of tropical cyclones with adjacent synoptic features (e.g., monsoon surges) frequently result in asymmetric wind distributions. ATCM predictions should lead to accurate predictions of these asymmetries.

Goal 5: The dynamical model must provide an accurate specification of the synoptic-scale flow surrounding the tropical cyclone. This includes the ability to accurately analyze and predict TUTT cyclones, monsoon surges, the monsoon trough, cut-off lows and other tropical and subtropical phenomena within JTWC's AOR.

Background: Erratic movement and frequently significant southward displacement are associated with cyclones interacting with a northeast monsoon surge in the South China Sea or the Philippine Sea. The present dynamical model analyses and predictions frequently fail to resolve TUTT cells or cut-off lows in the Northwest Pacific, which have a significant effect on cyclone movement and intensity. Monsoon depressions in the South China Sea routinely reach minimal typhoon strength without separating from the monsoon trough. The unique characteristics and movement of these systems are poorly treated by the dynamical models.

Goal 6: The ATCM should model the interaction of the cyclone with topography.

Background: Under strong mid-tropospheric flow, topography has little effect on the resultant movement of the cyclones. Topographical influences in these conditions are treated adequately with current objective guidance. Under weaker flow the cyclone movement is significantly influenced by the surrounding terrain and the resultant movement is difficult to predict with existing forecast procedures.

JTWC Operational Constraints

1) The initial model guidance on a tropical cyclone must be available on short notice and not depend on a lengthy track history. This requirement may be met with a different model such as OTCM.

Background: Often the initial forecast is both time critical and track critical. Small, intense cyclones can go undetected until they reach intensities of 40 to 50 kt. Because the main genesis regions in the Northwest Pacific are only 24 to 48 hours of cyclone movement from major DOD assets, irreversible decisions are occasionally made by customers based on the initial warning.

2) After the initial warning, routine 12-hourly model runs are adequate; the capability to make 6-hourly predictions would be required only in exceptional cases.

Background: Within JTWC's AOR, upper air data are available on a 12 or 24 hour basis. FNOC global model runs are also available once every 12 hours. Given these factors, little forecast variability in forecast tracks <u>should</u> be expected from more frequent model predictions.

3) FNOC should be capable of up to 6 model predictions within a 12 hour period in support of JTWC.

Background: JTWC has warned on a maximum of five systems at any given time. If FNOC is tasked to perform model predictions for other warning agencies, up to 10 simultaneous cyclones are possible. Multiple cyclones occur in JTWC's AOR approximately one third of the days of the year, so FNOC should expect two to three model runs per 12 hours on a routine basis.

4) There is not an optimum time of receipt for model predictions as long as they are timely, preferably less than six hours after synoptic time.

Background: JTWC warning times can and often are shifted in order to provide the most accurate and timely product and could be adjusted to accommodate model run times.

5) By ocean basin, JTWC priorities are the Northwest Pacific, South China Sea, Arabian Sea, Australian region, the South Indian Ocean and the Bay of Bengal.

Background: Because of the location of DOD assets, the overriding interest is in the Northwest Pacific, the South China Sea and the Arabian Sea. Every tropical cyclone in these regions will potentially impact on a DOD asset.

6) The final evaluation of the ATCM must occur in an operational forecast environment over a period of at least one year.

Background: There is a large variability in synoptic conditions and cyclone evolution by region, season, time of season and individual cyclone. Frequently an objective aid will perform very well for a series of cyclones for a single season, and then fail dramatically at another time. Also, forecast content can best be determined in an operational environment with the model predictions being used as a decision making tool.

Summary Comments

What JTWC needs from an ATCM:

1) Accurate 48 and 72 hour forecasts (at the very most 96 hours);
2) Identification of difficult forecast situations and reasonable skill in resolving these situations;
3) The reliable prediction of routine forecast tracks;
4) Asymmetry, intensity, and size prediction; and
5) High forecast content, which is defined as the ability to identify a changing track or intensity trend 48 to 72 hours in advance and reliably predict the new trend.

Constraints on the operation of the ATCM:

1) Predictions each 12 hours is acceptable,
2) Up to five predictions/12 h period for tropical cyclones in JTWC's AOR,
3) In some regions, satellite data will be the primary, if not the only, input; and
4) Model runs should not be based on 12 to 18 hour old fields as frequently happens now.

Comments on the Performance of the Nested Tropical Cyclone Model (NTCM) During the 1984 Northwest Pacific Tropical Cyclone Season

An updated version of the NTCM was available for use by JTWC during the 1984 Northwest Pacific tropical cyclone season. JTWC evaluated NTCM track predictions and gradually developed guidelines for operational usage of the NTCM. During the evaluation, several characteristics of the NTCM which limit its value as an operational forecast tool were revealed. The purpose of this paper is to identify those weaknesses and describe how the NTCM track predictions are used at JTWC.

NTCM Characteristics

1. NTCM predicted cyclone movement averaged approximately 40 percent less than observed cyclone movement. This is the most overriding feature of the current NTCM. Previous versions of NTCM have exhibited a similar bias but not as great. It is not clear whether the larger bias this season was due to model changes or seasonal variability.

This slow bias had three significant effects on NTCM track predictions:

a. Decision points in the forecast track (recurvature, etc.) were forecast too late to be of operational use to JTWC.

b. When the decision point or track change involved interaction with a transient system, the location was incorrectly predicted (i.e. longitude of recurvature) since the model "cyclone" was not moving at the correct speed.

c. NTCM right-angle errors were competitive with other objective track guidance, however, the angle between the observed track and the predicted track was generally greater than other objective guidance.

2. NTCM had less track consistency than other objective guidance. JTWC was unable to predict actual track changes using NTCM predicted track changes due to the high variability from one model prediction to the next.

3. NTCM had a significant "right" bias or northward bias on westward moving systems.

Operational Use

JTWC operational use of NTCM was designed specifically to take advanatage of NTCM's two statisitcal strengths: low 72-hour vector error and low right-angle error. JTWC plotted only the 72-hour forecast position and ignored the 24- and 48-hour positions. Initially this was used as an actual forecast position with a slight adjustment for the expected speed bias. As the effect of the speed bias on the NTCM "skill" became more apparent, another forecast technique evolved. The NTCM 72-hour position was used only as a verifying opinion on the OTCM forecast. If both models were in good agreement, the OTCM forecast was used with relative confidence. If the model predictions disagreed, then the forecaster was aware that the OTCM prediction was less certain and other objective and subjective techniques were used to verify the OTCM prediction.

Enclosure (3)

COMMANDER IN CHIEF, U.S. PACIFIC COMMAND
(USCINCPAC)
CAMP H.M. SMITH, HAWAII 96861-5025

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3140
Ser 2838
2 P 1984

To: Joint Chiefs of Staff (J3-ESD)

Subj: USPACOM Mid-term Tropical Cyclone Research Objectives

Encl: (1) Prioritized Listing and Brief Explanation of the USPACOM Tropical Cyclone Research Objectives

1. Enclosure (1) is a prioritized listing, with a brief explanation, of the USPACOM mid-term tropical cyclone research objectives. These objectives were identified by the Research Committee of the USCINCPAC 1984 Tropical Cyclone Conference and validated by this headquarters upon the recommendation of the Environmental Group for the U.S. Pacific Command.

2. With adequate support and funding, the objectives stated in enclosure (1) are considered attainable within the mid-term (8-10 years). They do, however, represent only the initial effort, the first step in improving the tropical cyclone capabilities from its present stagnation.

3. It is requested that the objectives stated in enclosure (1) be validated and submitted to the Military Services and the Under Secretary of Defense for Research and Engineering for inclusion in the DOD research programs. It is further requested that these objectives be submitted to the Office of the Federal Coordinator for Meteorological Services and Supporting Research for consideration by the Research Committee of the 39th Annual Interdepartmental Hurricane Conference.

JOHN V. COX
Major General, USMC
Director for Operations

Copy to: (w/encl)
CINCPACFLT (02M)
CINCPACAF (DOW)
CDRWESTCOM (APIN-WE)
NOAA/NWS PAC REG
NAVWESTOCEANCEN

PRIORITIZED LISTING AND BRIEF EXPLANATION OF THE USPACOM TROPICAL CYCLONE RESEARCH OBJECTIVES

*1. Track Forecasting. Forecasts of the direction and speed of movement, including recurvature and acceleration/deceleration, which consistently show a statistically significant reduction in the mean position error and variance for 24, 48, and 72 hour forecast positions, respectively.

2. Tropical Analysis and Forecast Improvement. Tropical analysis schemes, to include all source data, incorporated as part of a single global analysis system for the initialization of forecast models. Requires the improvement of a tropical capability in global models or the development of separate tropical forecast capabilities.

*3. Intensity Forecasting. The identification of changes or fluctuations in tropical cyclone intensity with definite skill at 6 hourly intervals out to 72 hours.

4. Statement of Data Requirements. Determination of the data, independent of collection platform or platform availability, required to support forecast models and programs of the 1990's. Data definition should include, but not limited to, the following:

a. Area coverage

b. Resolution (horizontal/vertical)

c. Timeliness

d. Accuracy limits

e. Spatial accuracy

*5. Wind Distribution Forecasting. A forecast depiction, with definite skill out to 72 hours, of the configuration and extent of the surface wind field around a tropical system, particularly with respect to the 30, 50, and 100 knot wind radii.

6. Decision Assistance Presentation Methods. Determining the most optimum method(s) of presenting tropical cyclone forecast/warning information to assist the wide variety of users in the decision making process.

*7. Wave Height Forecasting. A model or scheme to forecast tropical cyclone generated significant wave heights that shows definite skill out to 72 hours.

*8. Precipitation Forecasting. A model or method which shows definite skill in forecasting rainfall rates and/or total amount from a tropical cyclone over a particular area independent of local effects.

* - Denotes those objectives where consideration should be given to choosing between, or balancing, dynamic modeling and satistical algorithm development to insure a maximum contribution to forecast accuracy.

APPENDIX D

SUMMARY OF FLEET NUMERICAL OCEANOGRAPHY CENTER OPERATIONAL CONSIDERATIONS

Charles J. Mauck
Fleet Numerical Oceanography Center, Monterey, CA
and
Michael Fiorino
Naval Environmental Prediction Research Facility, Monterey, CA

There are three essential factors that must be considered in designing an operational numerical forecast system: 1) the computer system; 2) the model code; and 3) human factors. The first computing decision is what type of processing will be required, i.e. whether a scalar computer (e.g. CYBER 855) or vector computer (CYBER 205) is needed. The scalar processing capability of Fleet Numerical Oceanography Center (FNOC) will be upgraded significantly in 1985 from one (a CYBER 175) to four class-5 machines with the addition of CYBER 855's. Vector computing upgrades are less certain, but it is hoped that the CYBER 205 will be expanded from one to at least two pipes with an increase in central memory (from 1.5 to at least 2.0 million words). Central memory is the key factor that determines priority in the scalar machines, but Central Processing Unit (CPU) time, Input/Output (IO) and other peripheral processing should also be considered. Size can also be an important factor in the vector machine. The small core requirements of the Nested Tropical Cyclone Model (NTCM) allows co-processing during the Navy Operational Global Atmospheric Prediction System (NOGAPS) integration. A larger core requirement would have forced the NTCM to be run outside of the NOGAPS operational run and would have resulted in a degradation in terms of forecast timeliness.

A primary operational model consideration is maintenance and upgrades in the computer code. The programs will be maintained and executed by FNOC personnel who do not have a large amount of experience in the intricacies of numerical weather prediction. Thus, code that is well documented, modular, and easily modified is highly desired.

The operational model design considerations break down into four areas: 1) input; 2) model; 3) forecast initiation; and 4) output. The modelers must be aware of which analysis and forecast fields are available at various points in

the operational (OPS) cycle. The type and amount of storm information also changes during the OPS cycle. These input factors should be considered in the first stages of model development. There are numerous research forecast tools that had to be drastically modified because of a poor understanding of the FNOC data analysis/forecast cycle.

The numerical model may require updates during its forecast. The availability of update fields is also variable. For example, the NOGAPS forecast fields are maintained for only 12 h. If a 24 h old sequence of NOGAPS forecasts is needed, then provision will have to be made at FNOC to retain the necessary fields for a longer period. A model testing and evaluation factor that should be recognized is that all FNOC products and fields are not archived. Special or nonstandard archiving needs will have to be addressed separately.

Another operational model consideration is timing. There are many factors that determine when the forecast model can be run in the OPS stream, including: 1) the availability of inputs; 2) core requirements; 3) CPU time; and 4) the method and location of output. Communication can be a significant time sink, depending on the quantity and where the products are to be transmitted. The most important timeliness consideration is operational utility. If the forecast cannot reach the customers in time to be of use, it should not be included in the operational cycle. Fortunately, there is some flexibility in both the OPS stream and the forecast cycles of FNOC customers, but programs that are of "academic" interest only should not be run operationally.

A forecast model can be initiated in basically three ways: 1) by human beings 2) as part of the regular OPS stream and 3) in response to an Automated Response to Query (ARQ). The NTCM is initiated by the FNOC Quality Control Duty Officer (QCDO) whereas the One-way influence Tropical Cyclone Model (OTCM) is run via an ARQ. There are several reasons for the difference between the two types of model initiation. The current FNOC command policy is that there will be no ARQ's on the CYBER 205. Unlike the OTCM, which runs on the CYBER 175, the NTCM runs on the CYBER 205 and thus cannot be ARQ'ed. Differences in forecast procedures among the tropical cyclone forecast centers affects the availability of the input positions. The best solution for the NTCM was to have the QCDO manually initiate the model run -- a somewhat less than desirable method.

On the other end of the communication line is the user who must be able to understand the output. Decisions on what type of output should be transmitted

must be guided by more than science and communications limitations. The best solution is an output package that minimizes the amount of numbers transmitted, and has maximum forecast "content" as judged by the human forecaster.

Even though a new forecast tool can have very good science and computing features, the execution of the operational program must take into account the human factors involved in both input and output. First, the code should be "sailor" or "Murphy" proofed to the extent that the forecasts can be generated and transmitted with little or no human intervention. For instance, if the model "blows up" due to a bad observation, or bad storm inputs, the code should not have to rely on a computer operator to understand what happened or even know what to do. Rather, the program should exit gracefully and then prompt the operators as to the nature of the problem and send appropriate messages to the users.

In summary, the development of an operational forecast model must be guided by: 1) the type and amount of computing; 2) the availability of analyses and forecasts during the OPS run; 3) input methods and input data availability; and 4) human interaction in terms of program initiation and execution, and the user. Understanding of the FNOC operations will greatly facilitate operational implementation and testing and will lead to greater forecaster confidence and acceptance.

APPENDIX E

A BRIEF DESCRIPTION OF THE NAVY TROPICAL ANALYSIS AND THE NOGAPS ANALYSIS

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1.0 INTRODUCTION

This report updates and completes a set of notes on the tropical analysis which were prepared in January 1983 based on discussions with Fleet Numerical Oceanography Center (FNOC) personnel and on the reports of Grayson (1971), Lewis and Grayson (1972) and Lewis (1972). The analysis will be modified in the near future and I will describe those changes in a later section. However, most of the features of the tropical analysis still apply. The NOGAPS analysis notes are based on conversations with Drs. Ed Barker and Tom Rosmond.

2.0 THE NAVY TROPICAL ANALYSIS

The tropical analysis, which is commonly referred to as the the NVA (Numerical Variational Analysis) analysis, consists of two programs. The first analyzes surface pressure and winds and the second performs an upper air analysis of winds and temperature. The NVA analysis has been operational since 1973 and the archived fields have provided the "canned data sets" for testing the Nested Tropical Cyclone Model (NTCM).

2.1 SURFACE ANALYSIS

Although the final form of the surface analysis is displayed on a spherical global grid, it is actually a combination of two separate tropical and a midlatitude analyses. The NVA or tropical component, is performed every six hours on a global grid between 35N and 35S. There are three steps in the process. The first step is a three-pass successive correction (S-C) analysis for the pressure field. The first-guess field is the previous (6 h old) analysis -- effectively a persistence forecast. Geostrophic winds are then calculated from the analyzed pressures to provide the first-guess wind analysis for the second step. The u and v wind components are analyzed with the same S-C technique as

in the surface pressure analysis. In the last step, the NVA procedure insures a dynamical consistency between mass and momentum. The weighting factors in the NVA are specified so that the winds are only slightly modified by the pressure field.

The surface analysis cannot realistically portray the circulation of the tropical cyclone because of the paucity of storm-scale observations. FNOC has developed a procedure to force wind "data" into the analysis based on the observed maximum winds. This "bogussing" is done for more than cosmetic reasons -- the surface wind analysis drives the ocean wave models. Some representation of the surface wind field around tropical cyclones is obviously needed. The bogussing is confined to a relatively small area (< 600 km) around the center position, but the persistent first guess and other feedbacks can cause larger scale influences. As I will describe in the next section, the surface winds are also used to adjust the winds aloft. Therefore, it is possible for the FNOC bogussing to distort the synoptic forcing, even in the upper levels. We generally do not observe a great deal of contamination; however, in my review of Navy models (see Appendix F), I present a typhoon case from the 1984 season in which the bogussing may have had a large, negative effect on the NTCM track forecast. Other facets of the bogussing are described below and in the review because the FNOC storm bogussing is an issue that requires more discussion.

2.2 UPPER AIR ANALYSIS

The domain of the upper air (UA) analysis is from 40S to 60N and globally in the E-W direction. This is why the UA has been referred to as the "global band." The grid is a Mercator projection with a 2.5 deg spacing (approximately 150 n mi at 22 N), so there are 49x144 grid points on the grid. The UA analysis is run every 12 hours. Winds are analyzed at 700, 400 and 250 mb, while the temperature field is analyzed at 850, 500 and 300 mb. Planned changes to the system include the addition of two analysis levels -- 100 mb for winds and 150 mb for temperature.

The first guess is created in a two-step process. First, the first-guess field for both temperature and winds is simply the previous (12 h old) analysis, with a 5% return to a monthly climatology defined at three levels: 700, 300 and 200 mb. In the second step, this "preliminary" first guess is replaced outside

of the tropics (30N-60N and 30S-40S) with the analysis of the Navy Operational Global Atmospheric Prediction System (NOGAPS). From 30N to 15N and 15S to 30S, the NOGAPS analysis and the preliminary first guess are "blended" together to form the "final" first guess.

The first guess may be represented schematically as:

```
---------------------------------------------------- 60N
               CURRENT NOGAPS ANALYSIS
---------------------------------------------------- 30N
     "BLEND ZONE"  (NOGAPS + PRELIMINARY 1ST GUESS)
---------------------------------------------------- 15N
                 95% PREVIOUS NVA +
----------------------------------------------------- EQ
                   5% CLIMATOLOGY
---------------------------------------------------- 15S
                    "BLEND ZONE"
---------------------------------------------------- 30S
               CURRENT NOGAPS ANALYSIS
---------------------------------------------------- 40S
```

The observations are not vertically interpolated to the analysis levels. Rather, observations in a layer about an analysis level are assumed to be valid at the analysis level. For example, all wind reports in the roughly 325 mb to 500 mb layer are defined to be valid at the 400 mb level. Each observation is given a confidence rating, e.g., a rawinsonde report would be given more weight than a satellite-derived wind.

The next step in the UA procedure is a 2-D, three-pass S-C analysis from 35N to 40S with a gross error check based on the percent difference between the observations and the first guess.

At this point the analysis looks like:

--- 60N

CURRENT NOGAPS ANALYSIS

--- 35N

S-C ANALYSIS

--- EQ

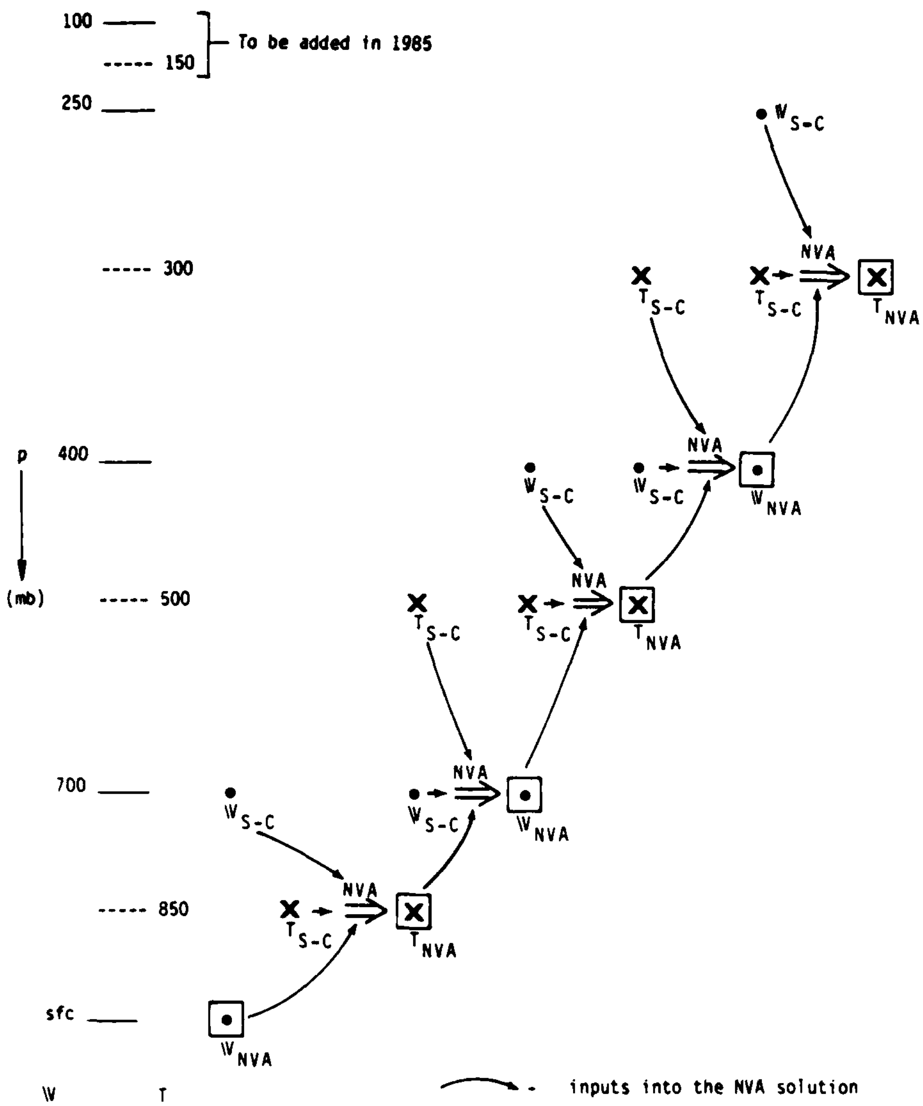
S-C ANALYSIS

--- 40S

The final step in the UA analysis is the NVA balancing. The NVA step only affects the vertical consistency between the winds and mass and is based on a generalized thermal wind relationship. The original idea behind the NVA step was to extend satellite cloud-motion vectors, which are more frequent in the upper and lower parts of the troposphere, into the middle levels.

The NVA procedure starts with the NVA surface winds and works upward, alternately adjusting the temperature and winds towards the generalized thermal wind values. The entire procedure is repeated or "recycled" to increase the vertical consistency.

A pictorial representation of the process is given below:



$\longrightarrow$ - inputs into the NVA solution

$\overset{NVA}{\Longrightarrow}$ - the NVA solution which comes from the minimization of

$$I = \int_V \left\{ \begin{array}{l} \tilde{\alpha}[(u-\tilde{u})^2 + (v-\tilde{v})^2] \\ + \tilde{\beta}[(T-\tilde{T})]^2 \\ + \alpha[F^2 + G^2] \end{array} \right\} dV$$

$(\ )_{NVA}$ - are the NVA analyzed values (the solution)

$(\ )_{S-C}$ - the S-C values

$\tilde{\alpha}, \tilde{\beta}$ - weighting factors on the difference between the solution and the S-C values

α - dynamical weighting factor

F - $\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial p}\right)$

G - $\frac{\partial}{\partial t}\left(\frac{\partial v}{\partial p}\right)$

F and G are zero, the winds and temperatures are in a thermal wind balance. Therefore, the larger α , the stronger the thermal wind constraint. Similarly as $\tilde{\alpha}$ and $\tilde{\beta}$ increase, the greater the forcing of the NVA solution towards the S-C analysis. The weighting factors have been specified to place a fairly mild thermal wind constraint on the winds and temperature. Thus, the NVA step will not cause large differences between the observations and the analysis. However, the scheme has been shown to extend the effects of upper and lower troposphere data into the midlevels, particularly at 700 mb (Lewis, 1972).

2.3 RECENT MODIFICATIONS AND UPCOMING CHANGES

The UA part of the tropical analysis was converted to a spherical format in 1984, i.e., the 60N - 40S analysis is now interpolated to the spherical grid of NOGAPS and poleward of 35N and 35S, the NVA analysis is replaced by the NOGAPS analysis with a 5 deg blend zone.

Pictorially, the "spherical" NVA looks like:

```
----------------------------------------- 90N
                  NOGAPS
----------------------------------------- 40N
                BLEND ZONE
----------------------------------------- 35N
               NVA ANALYSIS
----------------------------------------- 35N
                BLEND ZONE
----------------------------------------- 40N
                  NOGAPS
----------------------------------------- 90S
```

The major change to the UA part of the tropical analysis will be the addition of two new levels -- 100 mb for winds and 150 mb for temperature. The NVA balancing will then be applied to the 250 mb winds and the 150 mb temperatures, but only within the NVA region (35N to 35S). We do not anticipate a significant change in the overall quality of the analysis, except for a better representation of the upper troposphere. FNOC is also considering the possibility of generating a separate wind field for the ocean wave models so that the storm bogussing can be eliminated from the UA and surface analysis used by the tropical cyclone models.

2.4 COMMENTS

There are several features of the NVA that seem desirable for a tropical analysis system. In the absence of observations, the analysis will revert to climatology in approximately 20 days. This climatology is based on observations, whereas in a global-model, data-assimilation system the climatology is model generated. It is not clear if the observed climatology is really advantageous, but climatology does prevents the analysis from becoming grossly unrealistic.

The NVA analysis "draws" closely to the data and the effect of observations remains in the analysis over a period of a few days. However, this persistence feature could be detrimental when the observations are of a poor quality. Another potential advantage of NVA analysis is that observations are given greater weight than horizontal dynamical consistency, at least in the tropics.

Global model analysis systems assimilate data with dynamical constraints. While this is important for analyses and long-range global forecasts in the midlatitudes, we can not be certain whether "data" or "dynamic consistency" should be emphasized in the analysis component of the next-generation dynamical tropical cyclone forecast system. The approach taken with the NTCM is to build all initialization (balancing) procedures into the model.

3.0 THE NOGAPS ANALYSIS

NOGAPS has been operational at FNOC since 1982. It was anticipated that the analysis would appear too "noisy" for the field forecasters, so the smoother initialized fields were transmitted instead. Although the initialized fields are easier to interpret synoptically, they do not fit the observations as well as in the hemispheric analysis system prior to NOGAPS. The current NOGAPS analysis/initialization procedure attempts to alleviate this descrepancy.

NOGAPS uses a 6 h update cycle. The starting point of the cycle is a 3-D S-C analysis using all the observations within three hours of the analysis time. The first guess for the S-C analysis is the 6 h forecast from the previous cycle. Data acceptance is based on the difference between the observations and the first guess, with a fairly "loose" tolerance specified. A variational balancing procedure is then applied which: 1) constrains mass/momentum to obey the balance equation; and 2) minimizes the difference between the initialized and the analyzed vorticity and geopotential from the S-C step. Thus, only the non-divergent component of the flow is modified by the variational balancing. The unmodified divergent wind from the 6 h forecast is added to the balanced flow to complete the NOGAPS analysis/initialization procedure. These initialized NOGAPS fields are no longer transmitted to the field. Rather, the initialized fields are "re-analyzed" by applying a 2-D S-C step that forces the fields to more closely fit the observations.

Thus, three different NOGAPS fields could be used to initialize the ATCM: 1) the 3-D, S-C analysis; 2) the initialized fields after the variational adjustment; and 3) the 2-D re-analysis.

An optimum interpolation (OI) scheme is now being developed. Testing and evaluation will begin shortly with the goal of implementing the OI analysis operationally by the end of 1985.

4.0 CONCLUSIONS

This review has highlighted the most important features of the current global model analysis/initialization system and the tropical analysis used by the Navy. I believe there are advantages to both methods. The optimum analysis for the next-generation or Advanced Tropical Cyclone Model might be a combination of the two, but the Project Meeting should consider other alternatives. For example, we need to discuss the role of storm-scale observations in the large-scale analysis. Should a distinction be made between the two analysis problems (storm scale and the large scale), or should we analyze both scales simultaneously?

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APPENDIX F

A REVIEW OF THE DYNAMIC TROPICAL CYCLONE FORECAST MODELS DEVELOPED BY THE U.S. NAVY

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1.0 INTRODUCTION

The origins of the current dynamic tropical cyclone forecast models used by the U.S. Navy are found in the work of Harrison (1969). He developed a primitive equation model with parameterizations of the diabatic processes thought to be critical to the prediction of tropical weather events. The model was initialized with real data which included a slowly decaying tropical storm. One objective was to demonstrate that the model would not predict an uncontrolled development of the tropical cyclone. The 24 h prognoses were termed successful because the model remained stable with virtually no smoothing and produced synoptically reasonable forecasts of movement, precipitation and intensity change. An important observation was that "the frictionless adiabatic model appears to predict the movement of the storm at least as well as the diabatic scheme, for short-term prognosis." Harrison concluded that, "It must be also clearly shown that the complex and time-consuming (from a computational standpoint) diabatic scheme presently in use is capable of producing superior results." These comments have set the tone for much of the Navy model development. Harrison later developed the two-way interactive, nested-grid approach to increase horizontal resolution in a computationally efficient manner (Harrison, 1973). These two modelling efforts have become the dynamical "backbone" of all subsequent operational models, although the Navy effort included work on more advanced dynamic models.

In the mid 1970's, the Naval Research Lab (NRL) developed a split-explicit (SE) model which was tested on a small sample of tropical cyclones (Madala and Hodur, 1977). However, the early success of the Nested Tropical Cyclone Model (NTCM) (Harrison, 1981) led to a decision at NEPRF to apply the SE model to

midlatitude problems. This SE model is now known as the Navy Operational Regional Atmospheric Prediction System (NORAPS). One of the proposals for discussion in the Planning Meeting will be how to adapt a two-way version of NORAPS to the tropical cyclone problem. If this approach is adopted, we will have returned to the original purpose of the SE model, but after a great deal of valuable experience with the NTCM. I will now review the predecessors of the NTCM without presenting detailed descriptions of the models or the results. The purpose is to provide the necessary background information on the NTCM and indicate why an advanced model is required.

2.0 COARSE-GRID MODELS

Work with the three-grid, nested model (Harrison, 1973) continued in the early 1970's with the first attempts to initialize the model with real data. Besides the recognized need for dynamically based track forecasts, several hand-analyzed cases from the western Pacific (WESTPAC) were prepared by the Joint Typhoon Warning Center (JTWC) for experimentation. The initial tests were made with a coarse-grid version of the nested model (without the inner two grids) for computational efficiency and to simplify interpretation of the results. It turned out the the coarse-grid model forecasts were nearly as good as those from the nested-grid model (Ley and Elsberry, 1976). The coarse-grid version, without the inner nests, became know as the Channel Model because of the channel conditions on the northern and southern boundaries of the grid (Hinsman, 1977). The Channel Model, or what was called the Tropical Cyclone Model (TCM) by the JTWC, was the first-generation, coarse-grid model run at Fleet Numerical Oceanography Center (FNOC) and was run routinely starting in 1976. The results were fairly impressive, particularly in providing guidance on recurvature, although a wide variation in forecast skill was noted.

The TCM underwent several modifications in the late 1970's to become the One-way "interactive" Tropical Cyclone Model or the OTCM. One of the key differences between the OTCM and the TCM was the boundary conditions. Hodur and Burk (1978) applied the tendency modification strategy of Perkey and Kreitzburg (1976) to specify the time variations at the boundaries and they obtained an improved large-scale forecast. Improved track forecasts were also obtained, but it is uncertain if the time-dependent boundaries were the only reason because the change in boundary conditions had other impacts. The initialization (balancing) did not require an adjustment of the mean zonal wind as in the TCM

(Elsberry and Harrison, 1971) and the circulation near the storm was specified in terms of a symmetric vorticity bogus that weakly depended on storm intensity. More importantly, the "bias-corrector" was added in 1981. The bias corrector builds persistence into the dynamic model through a modification of the initial flow around the storm. This model (OTCM) has been in operations since 1979 and is now the preferred aid at JTWC for long-range guidance because of its proven consistency from 1979-1983 (Tsui, 1984).

The basic goal of the NTCM development was to exceed the skill levels set by the OTCM. Although the NTCM should have the potential for improvement over the OTCM, the operational results in 1984 have shown there are many deficiencies in the current NTCM system. The following review of the development of the NTCM will highlight these problem areas.

3.0 NESTED TROPICAL CYCLONE MODELS

Harrison chose to apply the two-grid version with a 5:1 reduction rather than the three-grid version with a reduction factor of 2:1 (Harrison, 1973). The outer (coarse) grid was initialized with the FNOC tropical wind analysis as in the TCM. A bogus tropical cyclone circulation was inserted into the flow of the inner mesh because of grid resolution and the inability of the data and/or the FNOC tropical analysis to define the storm. Harrison (1981) tested the model for 40 WESTPAC cases from 20 typhoons. The results were very impressive with median forecast errors of 78, 150 and 223 n mi at 24, 48 and 72 h, respectively. These error levels were much lower than typically found from other track prediction aids and further development was warranted. I will call this version NTCM1.0 because it is the starting point for the subsequent development.

Although the research version of NTCM1.0 made very good track predictions, the model would sometimes "blow up." The problem was traced to the formulation of the vertical advection term in the 1000-mb geopotential equation. A horizontal averaging of the vertical motion in the vertical advection term prevented the model from responding to the two grid-length noise that is commonly found with scheme A grids. This modified version (referred to here as NTCM1.1) was extensively tested on 220 cases in WESTPAC (Harrison and Fiorino, 1982). The mean forecast errors were lower than the corresponding JTWC scores, but the magnitude of the model's error had risen significantly from the preliminary results (e.g., 232 versus 317 n mi at 72 h).

3.1 OPERATIONS IN 1981

The forecast procedure of JTWC has changed considerably over the years. During 1981, the warnings were issued within a time window rather than at a set time. The "variable warning time" was intended to give the forecaster flexibility in using reconnaissance and synoptic data in preparing the warning. Consequently, JTWC would request their aids around synoptic time with a position valid at that synoptic time. For example, the 00 GMT warning would be supported by aids run with a 00 GMT position. The request for the 00 GMT aids would be received at FNOC within 1-2 h on either side of 00 GMT. The objective synoptic analysis for 00 GMT would not be available to run the models and to transmit the results to Guam before the forecasters made their warnings. The only alternative was to use a 12 h prog that was valid at the warning time (the 12 h forecast from 12 GMT in the example). Therefore, NTCM1.1 was run routinely for the 1981 typhoon season using prog fields instead of the analyses as in the 220-case development sample. See Appendix D for a description of the FNOC tropical analysis and the Navy Operational Global Atmospheric Prediction System (NOGAPS) analysis will be provided separately.

The key point is that a numerical model forecast specified the large-scale flow for the NTCM during 1981. The median forecast errors were significantly larger with this method of operation. Fig. 1 displays the 1981 results. NTCM(OP) is NTCM1.1 initialized with the progs and NTCM(ANAL) is the same model initialized with analyses. The forecast errors for JTWC are also given. The two models have comparable skill at 24 h, but by 72 h there is an approximately 30% increase in error due to the prog fields. The median errors for NTCM(ANAL) were nearly identical to those from the 220-case sample, but not as good as the JTWC scores. The OTCM was the best aid in 1981 (JTWC Annual Typhoon Report) with lower forecast errors than even NTCM(ANAL). Thus, the potential displayed by NTCM1.0 in the 40-case or the 220-case sample was not being realized in practice and that the model, and how it was initialized, was responsible.

3.2 MFM-NTCM COMPARISON

The importance of the large-scale fields used to initialize the model was clearly demonstrated by the comparison of NTCM(OP) and NTCM(ANAL). The NTCM was also initialized with the global analysis of the National Meteorological Center (NMC) as part of a model intercomparison study. The performance of the

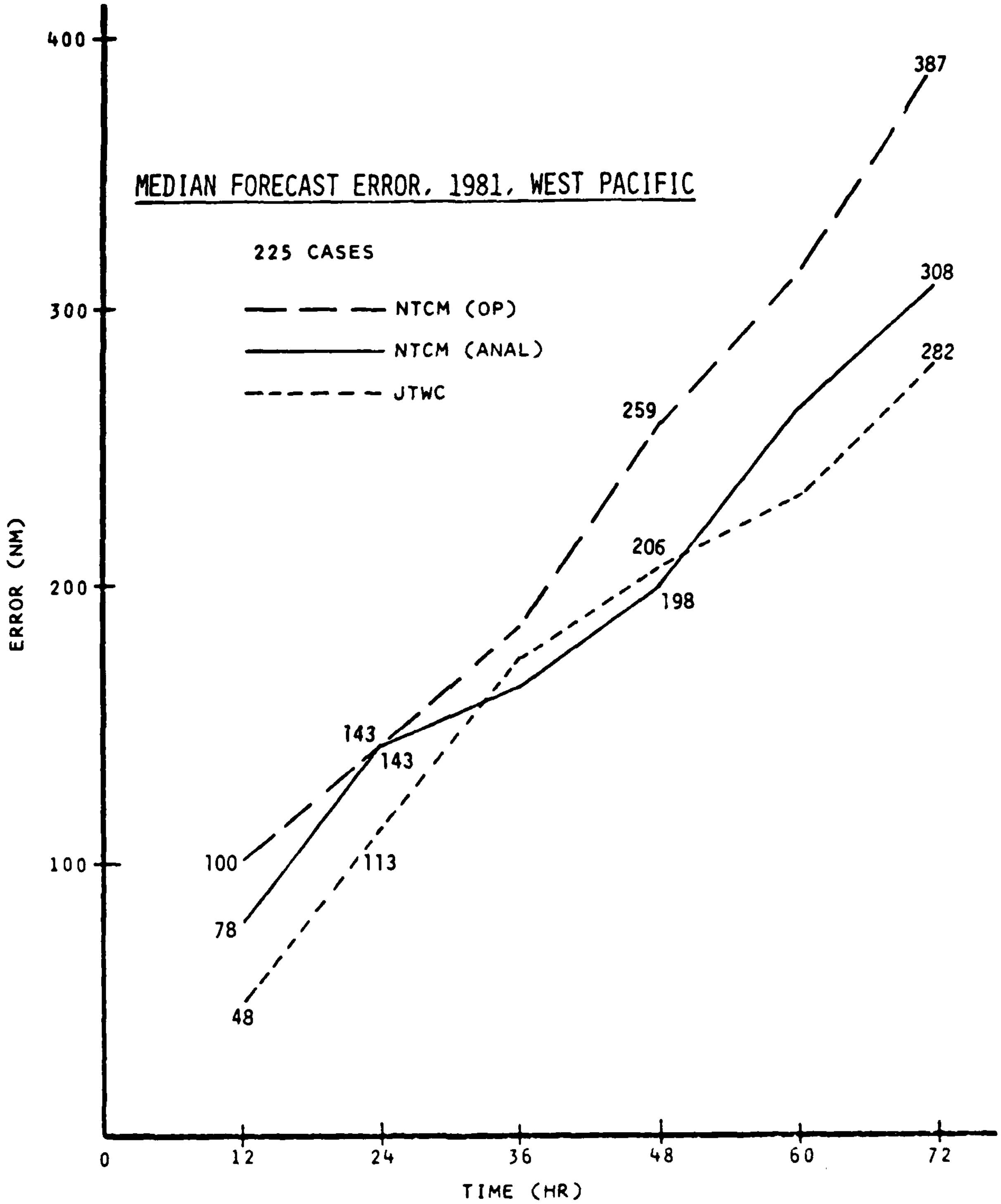

Figure 1. Median forecast error for the 1981 WESTPAC season. NTCM(OP) is NTCM1.2 using prog fields and NTCM(ANAL) is the same model but using the analysis. The official forecast errors of JTWC are also displayed. The comparison is homogeneous.

relatively simple NTCM was compared to the more sophisticated Moveable Fine-mesh Model (MFM) which had been used operationally for Atlantic (LANT) storms since 1975. Fig. 2 summarizes the features of the NTCM and the MFM, as well as the nested-grid model of the Japanese Meteorological Agency. The geographic orientation of the NTCM grids and the MFM is given in Fig. 3.

The results for 40 cases in the LANT are shown in Fig. 4. (Fiorino et al., 1982). Here we compare the two systems in the sense that each model is initialized with the corresponding analysis at that center and that the model/analysis is viewed as a separate entity. It appears that the NTCM and MFM systems perform at approximately the same skill level, at least to 48 h. These results, however, must be interpreted with caution. The 40 cases are not representative of typical LANT forecast situations as implied by the large improvement of the median forecast error over the long-term NHC averages. Furthermore, the number of cases is too small for significant statistical comparisons. The experiment does suggest, however, that the NTCM was not drastically inferior to the more sophisticated MFM.

We also ran the NTCM with the global analyses used by the MFM. The NMC fields were not generated with precisely the same analysis procedure for all cases because of the continual updating that occurs in any operational center. However, the NMC scheme was always global and used a global model to assist in the data assimilation, unlike the FNOC tropical analysis. The comparison of the two homogeneous sets of NTCM forecasts is shown in Fig. 5. We find a significant skill degradation of NTCM(NMC) versus NTCM(FNOC), which illustrates the profound effect of the large-scale analysis on model performance. Another significant finding of the study was the much slower motion of the NTCM using the NMC data compared to the FNOC runs.

Examination of the two analyses showed reduced amplitude of the wind features in the NMC analysis. We therefore compared the total kinetic energy in the coarse grid from the two analyses as shown in Fig. 6. There is roughly 25% less energy in the NMC winds than in the corresponding FNOC winds. This explains in part why NTCM(NMC) was slower than NTCM(FNOC), but does not explain why the MFM was unaffected. Apparently, the model determines part of the speed of movement, and that the large-scale flow is not the only factor in the track forecasts. Perhaps the MFM was influenced by the lower kinetic energy, but the dynamical-physical connection between the winds and the heating fields may have compensated.

OPERATIONAL DYNAMIC TROPICAL CYCLONE MODELS

1983

AGENCY	NOC/FNOC	NWS/NMC	JMA/ECC
MODEL	NESTED TROPICAL CYCLONE MODEL (NTCM)	MOVABLE FINE-MESH MODEL (MFM)	MOVING NESTED GRID (MNG)
GRID	3 LAYERS COARSE GRID ΔX = 205 KM 6400X4700 KM^2 FINE GRID ΔX = 41 KM 1200X1200 KM^2	10 LAYERS STORM GRID ΔX = 60 KM 3000X3000 KM	3 LAYERS SYNOPTIC GRID ΔX = 381 KM 10200X10200 KM SUBSYNOPTIC GRID ΔX = 190.5 KM 5100X5100 KM MESOSCALE GRID ΔX = 95.25 KM 2550X2550 KM STORM GRID ΔX = 45 KM 1275X1275 KM
PROJECTION	MERCATOR	LAT/LONG	POLAR STEREOGRAPHIC
BOUNDARY CONDITIONS	CG: CHANNEL FG: TWO-WAY INTERACTIVE	STORM GRID: ONE-WAY INFLUENCE	SYNOPTIC GRID: ONE-WAY INFLUENCE SUBSYNOPTIC-STORM GRID: TWO-WAY INTERACTIVE
PHYSICS	SPECIFIED ANALYTIC HEATING FUNCTION	EXPLICIT CUMULUS PARAMETERIZATION BULK-TYPE PBL	SPECIFIED ANALYTIC HEATING FUNCTION BULK-TYPE PBL
INITIALIZATION OF VORTEX	STANDARD 3-D WIND BOGUS	3-D SPINUP	BASED ON HAND-BOGUSED 500 MB D-VALUES AND SURFACE PRESSURE
TRACKING	FOLLOW MAX. VORTICITY IN LOWEST LAYER (850 MB) FG MOVES	FOLLOW MAX. VORTICITY IN LOWEST LAYER STORM GRID MOVES	FOLLOW MIN. SFC PRESSURE POINT SUBSYNOPTIC STORM GRIDS MOVE
ENGINEERING	DIFFUSING A FUNCTION OF BASIN/MONTH	NONE	BIAS-CORRECTOR VARIABLE HEATING FUNCTION
COMPUTER RESOURCES	38 SEC CY205	5400 SEC IBM 360/195	1500 SEC

Figure 2. Characteristics of the three operational dynamic tropical models. The three supporting agencies are the Naval Oceanography Command (NOC), the National Weather Service (NWS) and the Japanese Meteorological Agency (JMA).

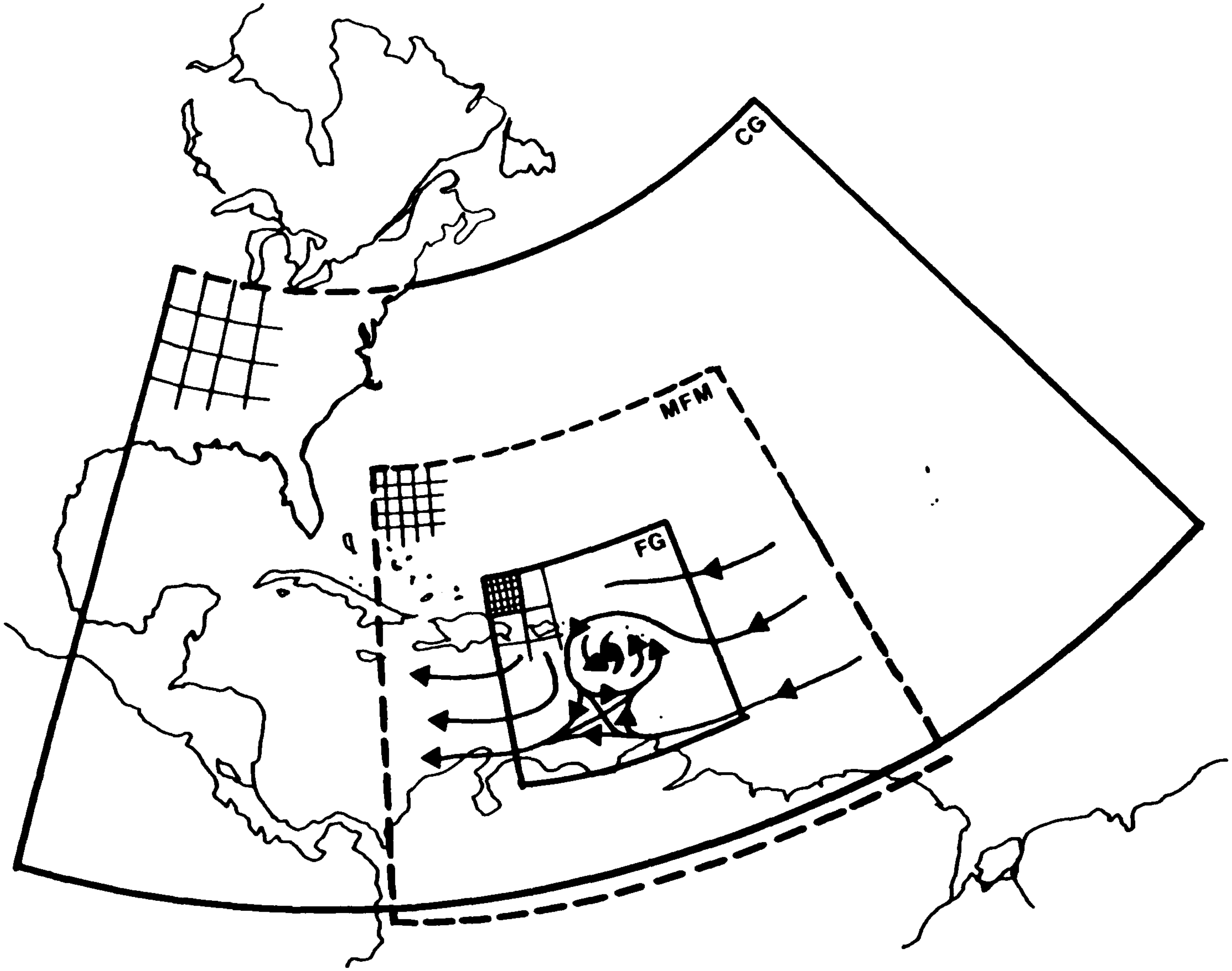

Figure 3. Geographical orientation of the two NTCM grids and the MFM mesh.

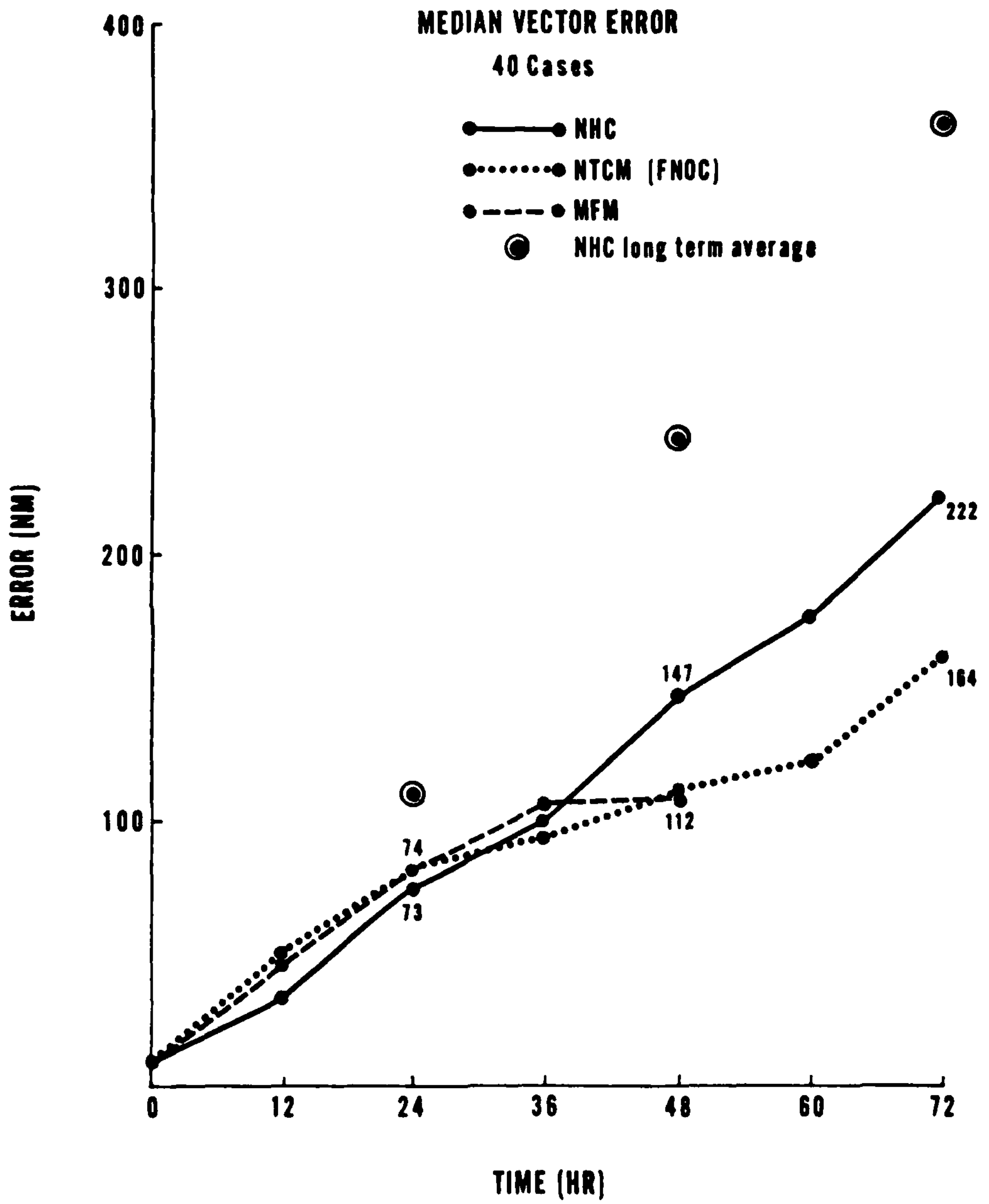

Figure 4. Median forecast error statistics from the MFM-NTCM comparison. The long-term average of the National Hurricane Center (NHC) are also displayed.

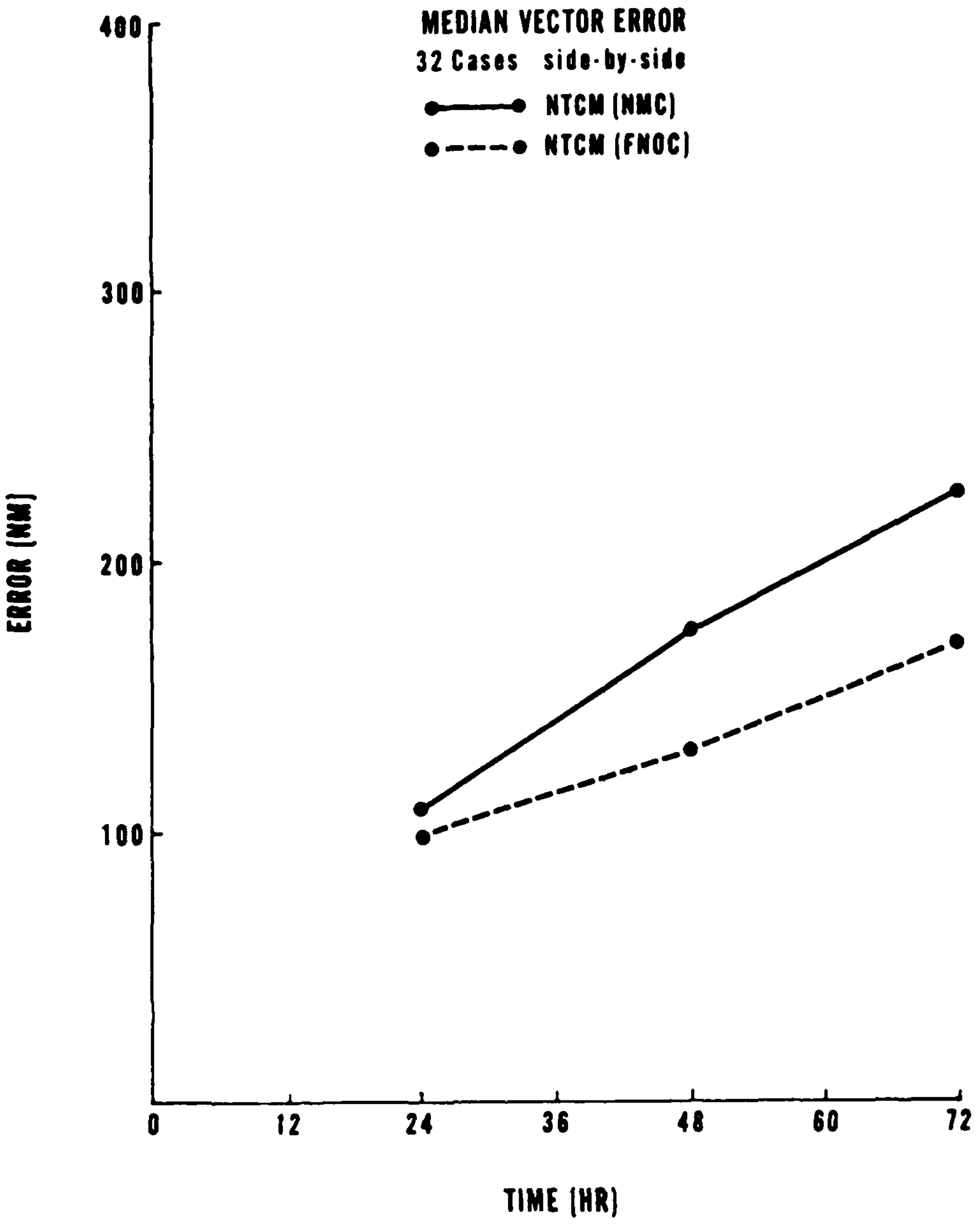

Figure 5. A homogeneous comparison of NTCM1.2 using the NMC global analysis (NTCM(NMC)) and the FNOC tropical analysis (NTCM(FNOC)).

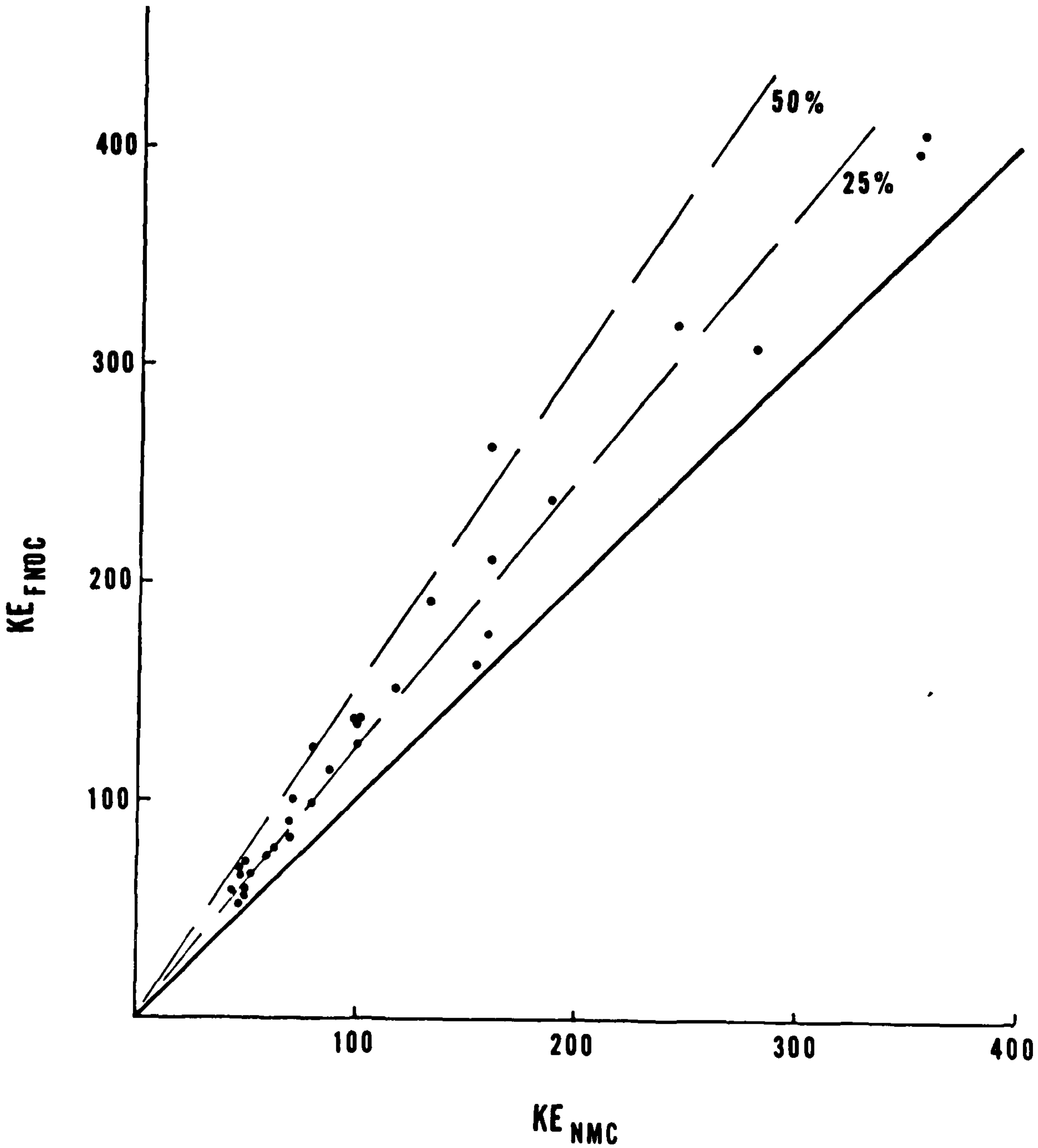

Figure 6. Total kinetic energy on the coarse grid of the NTCM from the NMC analysis (KE NMC) and the FNOC analysis (KE FNOC).

The MFM-NTCM comparison suggests that simply replacing the NTCM by a sophisticated model such as the MFM may not be "the" answer. Both approaches have merit and the Planning Meeting should include considerable discussion of the advantages and disadvantages of the two model systems.

3.3 TIMELINESS ASPECTS

A common complaint by the tropical cyclone forecaster is that the dynamic models are received much later than the other aids, which makes the assimilation of the dynamic guidance inconvenient or impossible in many cases. Several options are available for improving timeliness. The OTCM is currently run from the most recent 6-18 h forecast fields. This approach was not tried because of the degraded skill during the 1981 season when the NTCM was initialized with progs (see discussion in Section 3.1). An alternative is to use an "old" analysis with a current position. Harrison reran the 220-case set using a bogus storm circulation at the +6 and the +12 positions within the +0 large-scale analysis. For instance, the 18 GMT position would be run using the 12 GMT analysis, and the 00 GMT position would also use the previous 12 GMT analysis fields. He found that a 6 h difference between the analysis and the storm position had no effect on the 72 h skill of the model compared to a 0 h difference. A 12 h difference resulted in a 5-10% degradation. The NTCM is now run with the time offsetting as described above. I will postpone the discussion of the current schedule and how skill was affected until the section on the latest version of the model, but Harrison's finding is operationally very significant.

3.4 INITIALIZATION AND MODEL IMPROVEMENTS

Several coding errors were found in NTCM1.1 and the corrected version (NTCM1.2) was run routinely in 1982 using the analysis fields, but without the time offset. Results in WESTPAC were better than in 1981 vis-a-vis the other aids, but still not as good as the OTCM, especially at the 24 and 48 h forecast times. A perception of reduced skill in these early time periods decreased forecaster confidence and acceptance.

The NTCM experiments of Peak and Elsberry (1984) in the Southern Hemisphere revealed an "instability" at the northern boundary, or in the tropics for southern hemisphere tropical cyclones. The instability appeared to be related to a "slosh" in the wind along the boundary. The problem was eventually traced to the initialization (balancing) of the coarse grid.

The balancing procedure of NTCM1.2 used the observed (analyzed) winds, the 1000-mb geopotential and the temperatures at all levels. The geopotential was hydrostatically calculated from the 1000-mb geopotential and the temperature, but only at the lateral boundaries. The reverse divergence equation was then solved for the mass in the interior given these boundary conditions (Dirichlet problem). The observed temperatures were replaced with hydrostatically derived values from the balanced geopotential to complete the procedure.

There were two problems with this method. The first was related to the observed temperatures. We have occasionally observed superadiabatic profiles in the lower layers of the FNOC tropical analysis. Although the NTCM might be able to handle the unstable lapse rates, the presence of the superadiabatic layers implied a general problem with the temperature analysis. The second was the possible inconsistency between the observed mass and the winds at the northern and southern boundaries due to the imposition of the channel conditions (insulated, free-slip).

A new initialization procedure was developed that not only built the channel conditions directly into the balanced mass field, but removed any dependence on the observed temperature field. The change was motivated by dynamical considerations (winds dominate the adjustment process in the tropics) and the just-mentioned uncertainties in the FNOC tropical temperature analysis. The new initialization procedure reduced the slosh and produced a mass field in better balance (smaller ageostrophic winds) than the old scheme. Other modifications were made to NTCM1.2 model and to the treatment of the input data from the analysis. The resulting model is called NTCM2.0. Fig. 7 summarizes the changes in some detail. NTCM(1981) refers to NTCM1.2 and NTCM(1982) refers to NTCM2.0.

NTCM2.0 was extensively tested. The five types of tests included: 1) model sensitivity; 2) predictability; 3) sensitivity to the FNOC tropical analysis versus the NOGAPS global analysis; 4) worldwide application (the eastern Pacific, the Atlantic, the Indian Ocean and the Southern Hemisphere); and 5) observed storm motion addition via the "bias corrector" (Shewchuk and Elsberry, 1978).

A. MODIFICATIONS TO THE NTCM

	NTCM(1981)	NTCM(1982)
INPUT DATA	$\vec{V}_{850} \leftarrow \vec{V}_{SFC}$	$\vec{V}_{850} \leftarrow \vec{V}_{700}$ & $\vec{V}_{SFC}$
MODEL	$\frac{\partial\phi}{\partial t} = - \nabla \bullet \phi\vec{V} - \bar{\omega}\frac{\partial\phi}{\partial p}$	$\frac{\partial\phi}{\partial t} = - \vec{V}\bullet\nabla\phi - \omega\frac{\partial\phi}{\partial p}$

Figure 7a. Description of the changes to NTCM1.2 to make it NTCM2.0. Panel A gives the model and input data modifications and Panel B the initialization improvements. NTCM(1981) is NTCM1.2 and NTCM(1982) is NTCM2.0.

B. INITIALIZATION

NTCM (1981)	NTCM (1982)
1 NO β TERM	1 β TERM INCLUDED
2 GRID SAME AS COARSE GRID	2 EXPAND GRID IN E-W DIRECTION USING CYCLIC CONTINUITY
3 SOLVE $\nabla^2\phi = F(x,y)$	3 SOLVE $\nabla^2\phi = F(x,y)$
4 BOUNDARY VALUES OF ϕ FROM OBSERVED $\phi_{1000}, \theta_{850}, \theta_{1000}$ (DIRICHLET PROBLEM)	4 $\frac{\partial\phi}{\partial n} = -fu$ ON N-S BOUNDARIES, CYCLIC CONTINUITY IN E-W DIRECTION (NEUMANN PROBLEM)
5 $\bar{\phi}$ OBSERVED	5 $\bar{\phi}$ FROM TYPICAL VALUES
6 θ_{1000} & θ_{850} OBSERVED	6 θ_{1000} & θ_{850} DERIVED FROM θ_{700} AND TYPICAL SOUNDING

Figure 7b. Modifications to the NTCM (cont.)

3.5 SENSITIVITY EXPERIMENTS

The sensitivity experiments can be grouped into three categories according to model response to: 1) the physical parameters and vortex initialization; 2) numerics; and 3) errors in storm position due to operational procedures. Each set of experiments resulted from some problem discovered during the case-building phase of the development in which we gave the highest priority to running a large number of cases (200+). The results reported here should be considered as tentative. Nevertheless, we believe our findings will help to more clearly define the problem areas requiring additional research.

3.5.1 INTENSITY

We suspected that some of the variation in the skill of the track forecasts may have been related to the 60-kt bogus used for all situations. The 40-case sample from the MFM-NTCM comparison was chosen to test sensitivity to initial storm bogus intensity. There was a wide range in the observed initial maximum winds (135 to 30 kt) in the sample. The storm bogussing procedure in the NTCM places the maximum winds one fine grid point (41 km) from the center and then linearly interpolates between these "storm" winds and the flow at the 400-km radius. This method assumes that the inner core is independent of the environment and that the vortex contribution to the flow outside the eye decreases radially outward. The storm winds also decrease with height. However, changing the storm winds will not change the structure of the bogus circulation. That is, the pattern of the bogus is unchanged because the 400-km interpolation radius is retained. We found little sensitivity to the observed intensity versus the "standard" 60-kt storm in the 40-case LANT sample. There are several possible reasons. As just mentioned, the structure (e.g., radial variation of vorticity) was not influenced in a significant manner by the magnitude of the storm winds. Second, and more importantly, the analytic heating function that maintains the tropical cyclone circulation was the same in all the runs.

Experiments with idealized flow environments have shown that the model storm reaches a steady state after roughly 24 h of integration. That is, the initial vortex is transformed in the first 24 h into a nearly steady-state vortex and there is little variation after the transformation. This result was not known at the time of the intensity experiments. Although the NTCM is not sensitive to the initial intensity of the vortex, the model is sensitive to the storm simulation as controlled by the heating profile and horizontal diffusion.

3.5.2 HEATING

A 225-case sample of tropical cyclones from the 1981 WESTPAC typhoon season was used in tests of varying the heating magnitude and the amount and type of diffusion. However, there was no attempt to match intensity or size of the real storm to the imposed heating. The horizontal and vertical distribution of the heating, which determines the structure of the model storm, was not modified. Therefore, the heating experiments only measured sensitivity to vortex intensity and strength (maximum vorticity in the inner core), not to size. Physical reasoning (e.g. Holland, 1983) would suggest that size is the most important structure factor in the motion process. In retrospect, we would have achieved a greater response by varying the horizontal distribution of the heating. Nevertheless, how the heating forces the vortex evolution is controlled, in part, by the vorticity damping effect of momentum diffusion.

3.5.3 DIFFUSION

Variations in the magnitude and formulation of the momentum diffusion operator (Fig. 8) produced the greatest sensitivity of NTCM2.0 in terms of long-range skill (Fig. 9) The probable explanation is that diffusion affects vortex size. The median 24 h forecast error was improved in every version of NTCM2.0 over NTCM1.2, but little variation was found with the diffusion and heating changes. The initialization of NTCM2.0 was responsible for the improvement in the 24 h statistics. The physical parameters had their greatest effect on the 72 h performance of the model. Notice the 10-15% variations in the 72 h statistics relative to the near constancy of the 24 h errors. None of the separate versions were as good as NTCM1.2 at 72 h. We should also acknowledge that the variations are not strongly significant in a statistical sense.

We also found that the low diffusion version (LODF6.0) produced better forecasts in the "summer" months of August and September than the other versions, whereas the higher diffusion model (HIDF6.0) was best in the remaining months. The operational version of NTCM2.0 lowers diffusion during August and September in WESTPAC based on this result. Fig. 10 displays the overall performance comparison. Again, NTCM81 is NTCM1.2 and NTCM82 is NTCM2.0, but with the seasonally varying diffusion. Although NTCM2.0 is somewhat less skillful (not statistically significant) than NTCM1.2 at 48 and 72 h, the improved skill at 24 justified its acceptance as the version to run operationally. Further, as seen in Fig. 10, this new model was forecasting better than the older version (NTCM1.2) that had been run in 1981.

SENSITIVITY EXPERIMENTS

	MODEL VERSION	COMMENTS
1	NTCM81	1981 VERSION OF THE NTCM 1.2
2	HIDF6.0	SAME PHYSICAL PARAMETERS AS NTCM81 BUT WITH NTCM82 MODIFICATIONS (NTCM 2.0)
3	HIDF7.5	INCREASE STORM HEATING BY 25%. OTHERWISE SAME AS HIDF6.0
4	LODF7.5	DECREASE DIFFUSION ON THE FINE GRID SO DAMPING RATE IS THE SAME AS ON THE COARSE GRID. OTHERWISE AS HIDF7.5
5	LODF6.0	HEATING RATE THE SAME AS IN HIDF6.0
6	4TH6.0	SAME AS LODF6.0. BUT WITH 4TH ORDER DIFFUSION
7	4TH7.5	SAME AS 4TH6.0. BUT WITH SAME HEATING AS LODF6.0

Figure 8. Description of the heating and diffusion sensitivity experiments.

MEDIAN FORECAST ERROR (NM)
1981 WESTPAC - 225 CASES

MODEL	24 HR	72 HR
NTCM81	143	308
HIDF6.0	133	342
HIDF7.5	133	341
LODF6.0	130	312
LODF7.5	134	316
4TH6.0	133	323
4TH7.5	133	350
JTWC	113	282

Figure 9. Median forecast errors from the physical parameter sensitivity test. The models are described in Fig. 8.

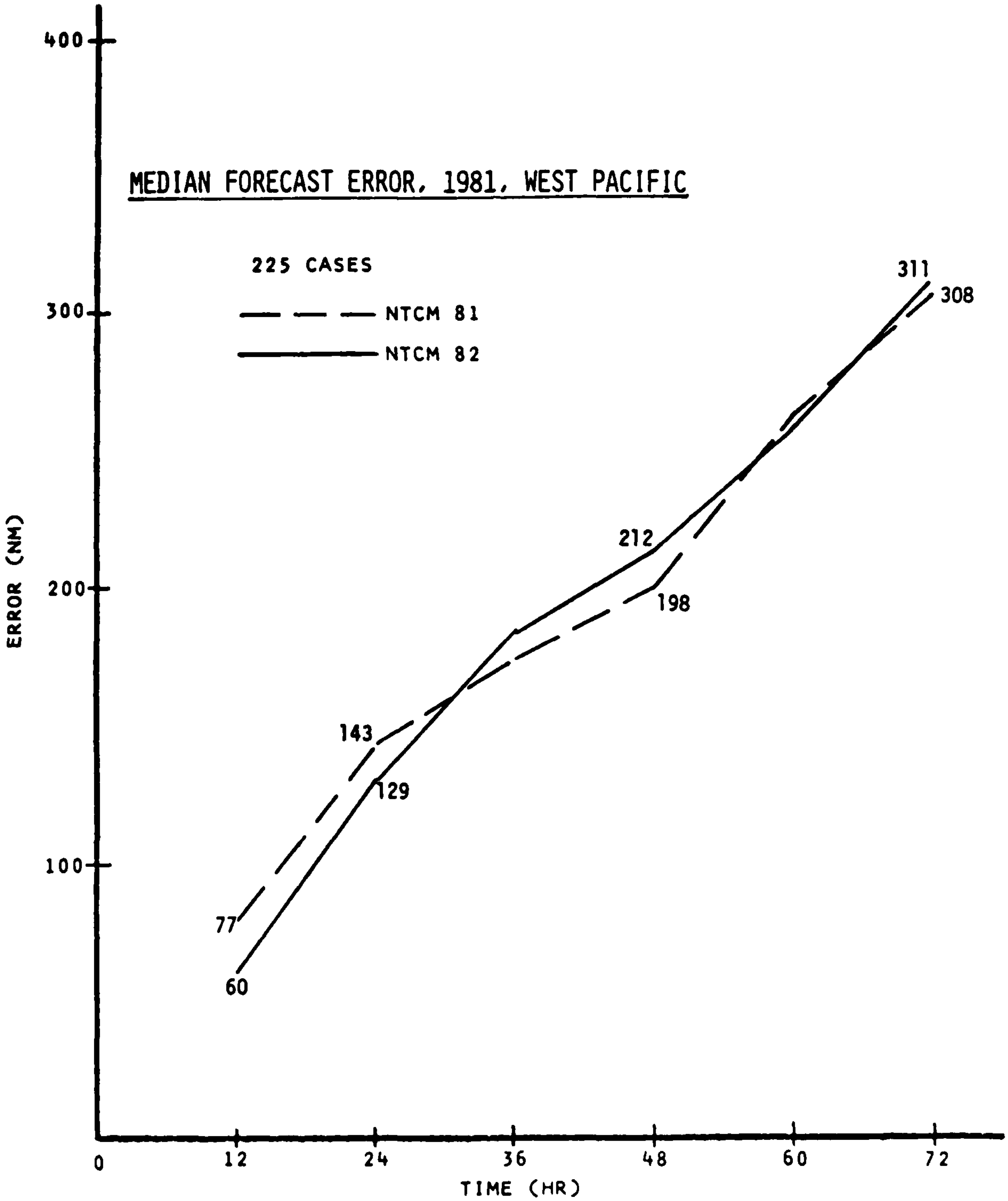

Figure 10. Median forecast errors for NTCM1.2 (NTCM 81) and NTCM2.0 (NTCM 82). NTCM2.0 uses a different diffusion coefficient in the summer (AUG and SEP)

Fig. 11 exemplifies how diffusion changes affected the track forecasts for two tropical cyclones in the beginning of the 1982 WESTPAC season. Lower diffusion (LODF) resulted in more northward movement (MAMIE in Panel A) and greater speed (NELSON in Panel B). Also observe how the differences between the high and low diffusion tracks grows in time.

In summary, the initialization had the biggest effect on the short-term forecasts while the physical processes of heating and diffusion had the greatest impact on the longer range forecasts (48-72 h). These experiments represent a first-order evaluation of the role that various modeling choices have in model skill. One of the goals of the Project Meeting should be the development of a comprehensive plan to test sensitivity to both model parameters and the initial analysis.

3.5.4 CHANNEL BOUNDARY CONDITIONS

The channel boundary conditions used on the coarse grid have been highly controversial because the one-way influence approach is thought to be far superior. Although this might be true meteorologically because of the information-addition property of the one-way method, there are mathematical and operational advantages to the channel conditions. To establish that the channel conditions were not degrading model skill, we performed two sets of experiments.

In the first set, we extended the model integration to five days (120 h) for 50 cases to determine if boundary effects grew in time, especially as the inner grid approached the sides of the coarse mesh. Storms were selected if the ending point of the five-day paths was near the lateral boundaries in both the N-S and E-W directions. The channel conditions did not have a significant effect on skill as seen in Fig. 12. When the model forecast was good at 72 h, the 120 h forecast were also generally good, in spite of the lateral boundaries.

Another way to minimize the effect of the boundaries is to expand the domain of the coarse grid. One of the complaints made by JTWC was that the coarse grid was not large enough to contain all of the initial synoptic features that might affect a tropical cyclone in WESTPAC. Based on guidance from JTWC, we reran the cases from the 1982 season with a coarse grid that was expanded from approximately 4200x6400 km to 5400x10000 km. All other aspects of the model remained the same. Fig. 13 presents the results. Although the forecast errors are generally the same, there are some curious differences.

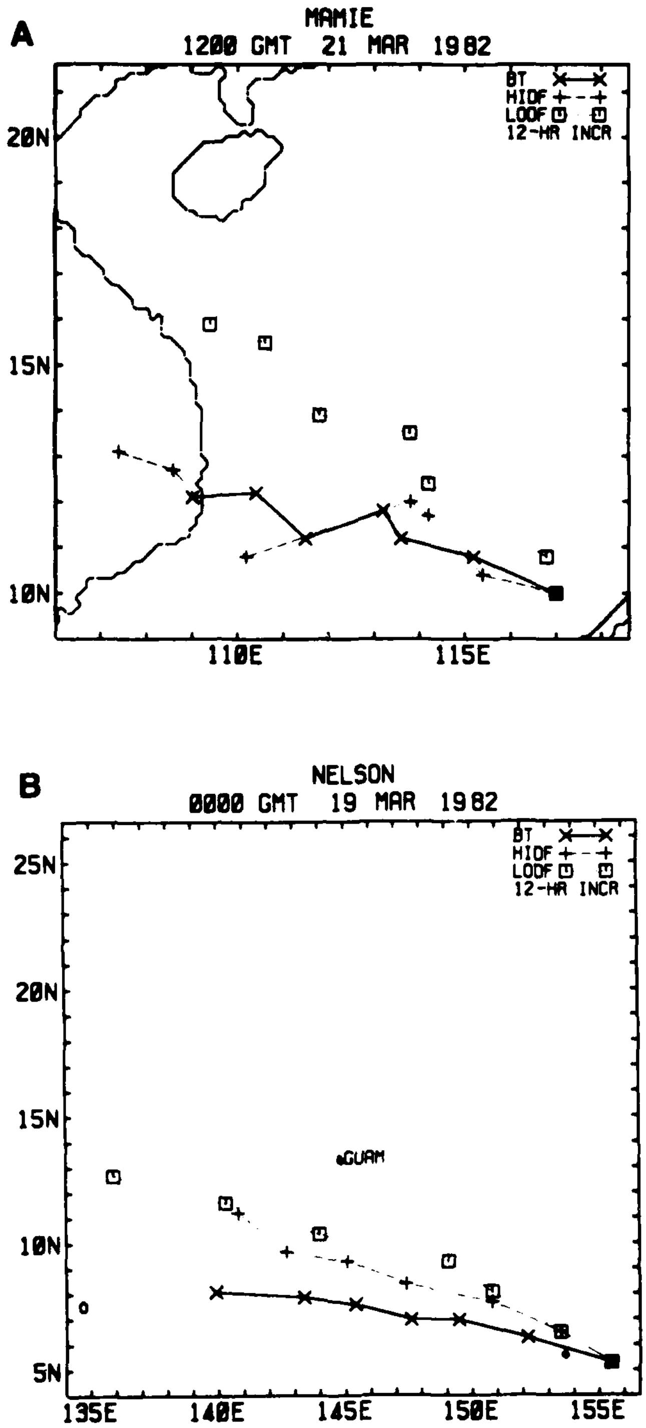

Figure 11. Two typhoon cases from 1982 WESTPAC season illustrating how changes in diffusion on the fine grid affects track. LODF is run with lower diffusion ($5.0 \times 10^4 m^2 s^{-1}$) and HIDF is higher diffusion forecast ($2.5 \times 10^5 m^2 s^{-1}$).

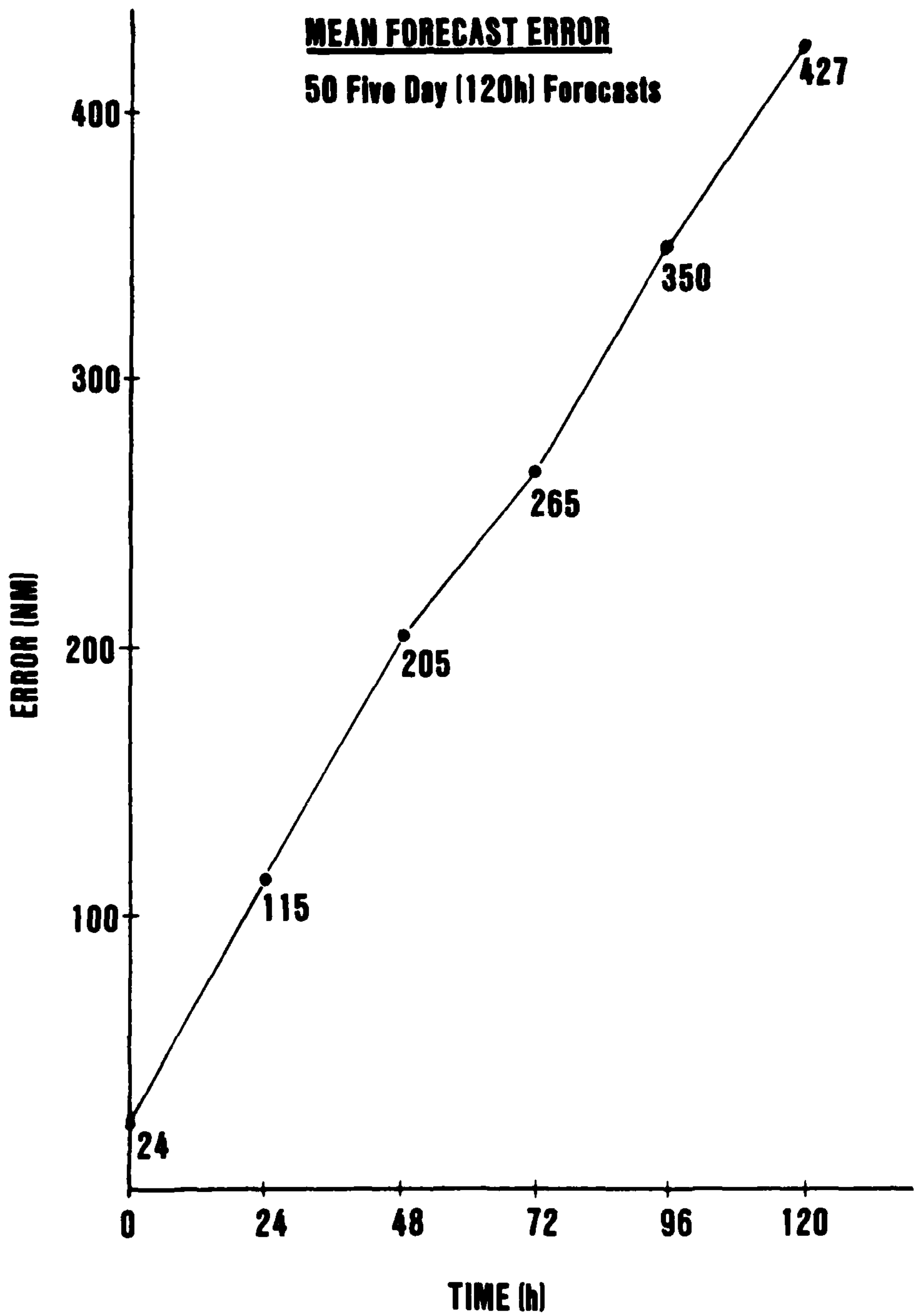

Figure 12. Mean forecast error for 50 five-day integrations. Each cases has a 120 h verifying position.

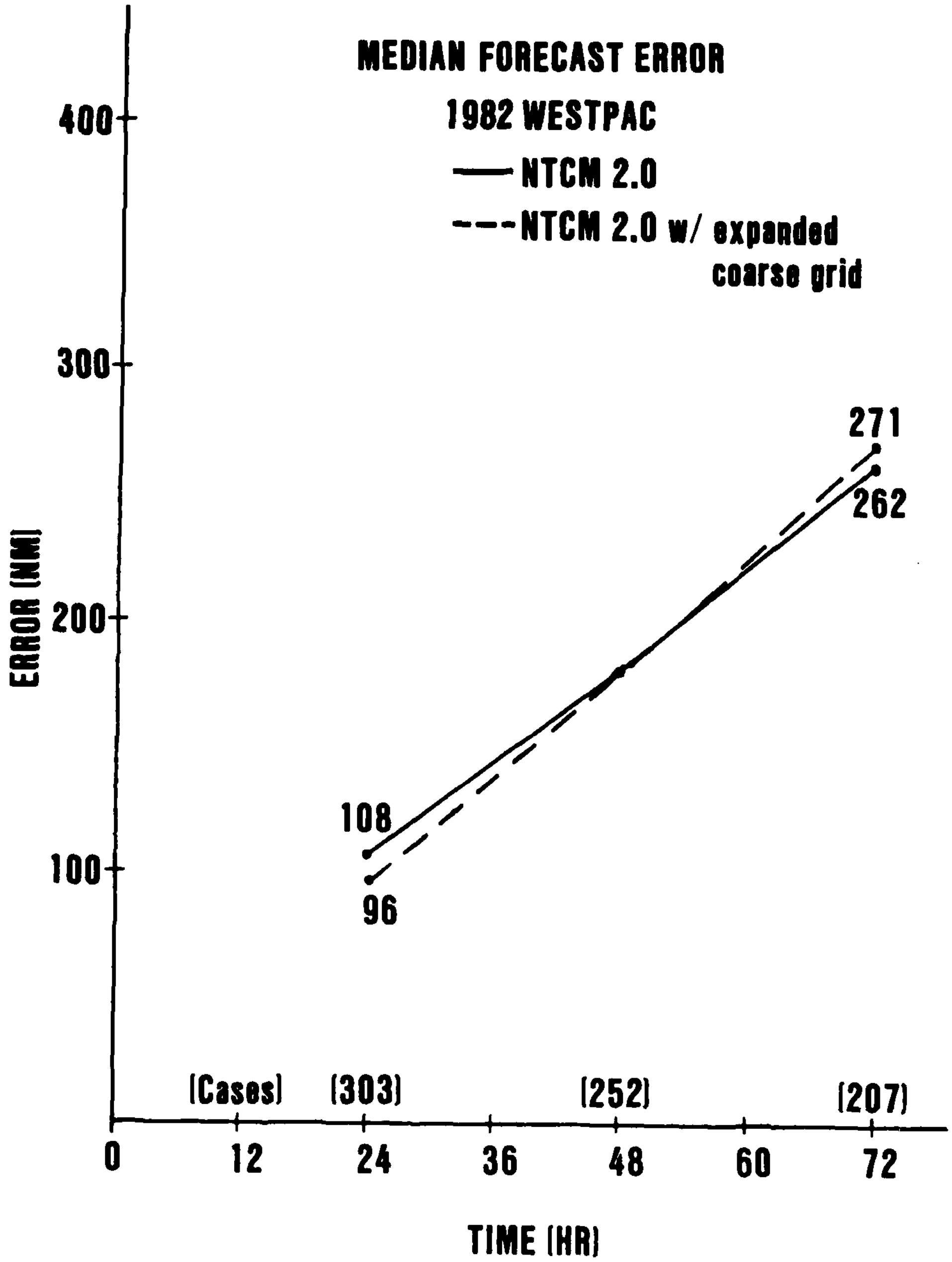

Figure 13. Median forecast error for expanded grid test.

The 24 h skill with the expanded grid was better than with the regular gird. My interpretation is that the initial balance around the storm was improved by placing the boundaries further away. It appears that the channel conditions used in the NTCM2.0 initialization procedure have a larger impact on the divergence equation solution for the balanced mass field than might be expected.

The somewhat poorer skill with the expanded grid at 72 h is difficult to understand. The magnitude of the speed bias in the expanded grid runs was slightly smaller than for the normal grid. It may be that the lower forecast errors resulted from the slower forecasts with the regular grid and that much of the "skill" of the NTCM may be directly attributable to the speed bias. However, these results show that the channel conditions do not have a large effect on model performance. This is not to say that the one-way influence approach might not lead to even better forecasts.

3.5.5 MAP SCALE FACTOR

The NTCM grid uses a Mercator map projection. The map factor varies only in the N-S direction and for a typical NTCM run would range from approximately 0.95 to 1.3. To save as much as 30% on computer run time, we used a constant map scale factor of 1.0. Although the mass and momentum fields would be internally consistent with a constant map factor, distortion of the fields when compared to analyses might be possible, especially in the midlatitudes.

We included the variable map scale factor in the model and reran the 1982 WESTPAC season with both a constant and a variable map factor (Fig. 14). The NTCM performs slightly better with the constant map factor. What is more interesting is that both the magnitude of the speed bias and the forecast error increased, in contrast to the expanded grid results. The speed bias difference between forecasts with and without a variable map factor was much greater than in the expanded grid experiments. Some slowness is desirable in reducing forecast error, but there is a limit. A more important issue is how the varying map scale factor reduced skill and slowed the model storm. One possibility is that the map factor affected the propagation of waves in the midlatitudes. However, it is troublesome that a correction to the model could reduce skill.

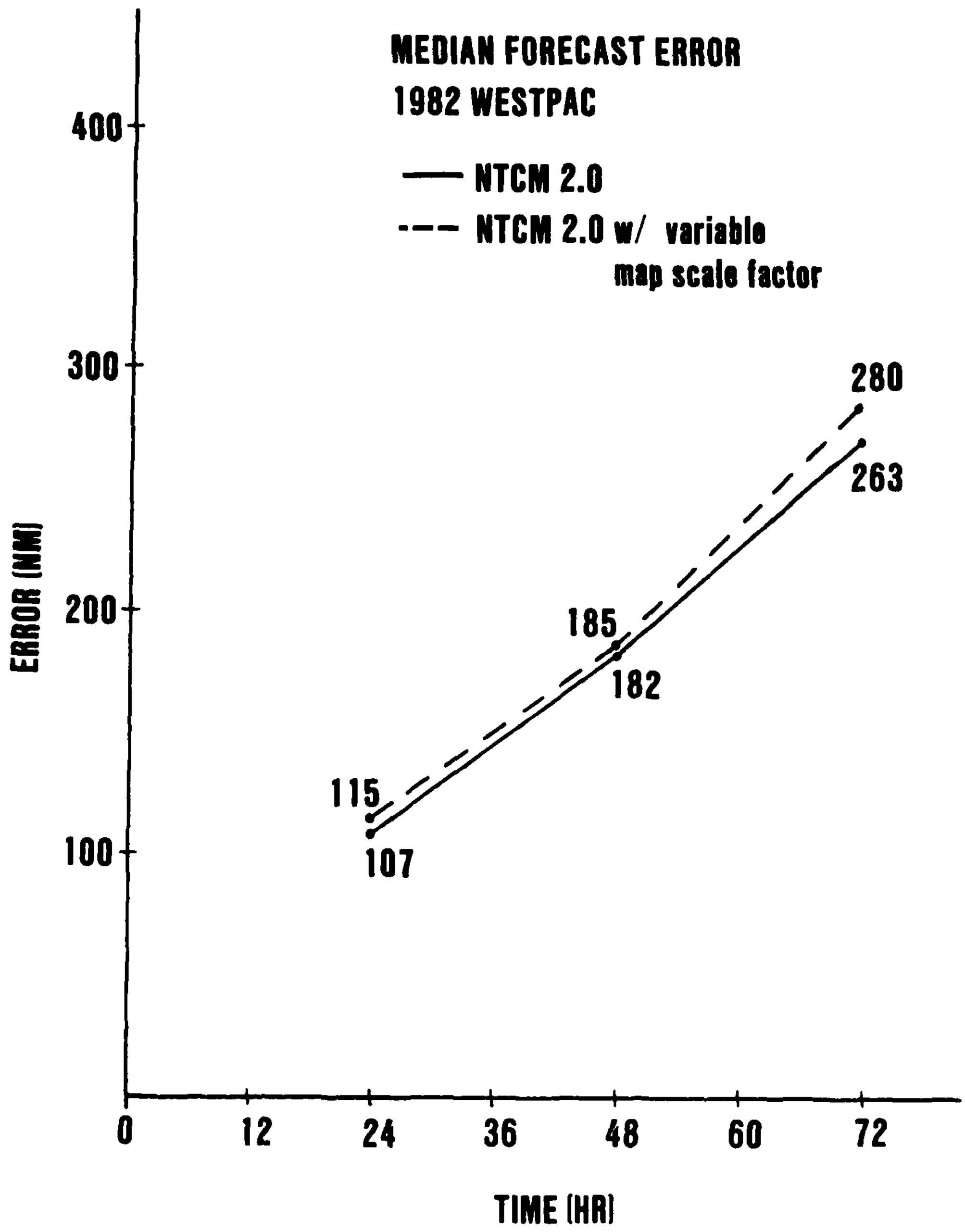

Figure 14. Median forecast error for the variable map scale factor test.

3.5.6 INITIAL POSITION

Operational schedules at the forecast centers and communication shortcomings often prevent FNOC from running the NTCM with the position the forecasters would desire, so we needed an assessment of how initial position errors affect model skill. The Eastern Pacific Hurricane Center (EPHC) was very concerned about the way FNOC derived the current storm position from a 6 h old EPHC warning through an interpolation between the 6 h old warning position and the 12 h EPHC forecast. For example, the 00 GMT FNOC position would come from the 18 GMT warning position and the 12 h EPHC forecast valid at 06 GMT. The EPHC forecasters felt that NTCM skill would be compromised with a less than accurate initial position. We conducted a simple and limited test.

Twenty cases from the eastern Pacific (EASTPAC) were chosen based on the length (speed) of the observed track and the track type (recurver, staller, etc.). The FNOC-derived position was perturbed one degree of latitude and longitude in the N-S and E-W direction to give five model integrations. All other aspects of the model runs were the same. Fig. 15 shows two representative cases. BARBARA was a fast-moving straight runner, while FLOSSIE took a erratic track toward the NW. The verifying track comes from the warning positions. The "swarm" of initial positions is shadowed to show distortion at 72 h. Although the pattern is somewhat contorted, the key point is that the swarm does not appreciably spread, as might be expected, and in fact contracted slightly in the mean. It thus appears that the long-term track of the NTCM is not overly sensitive to the initial position, at least in EASTPAC.

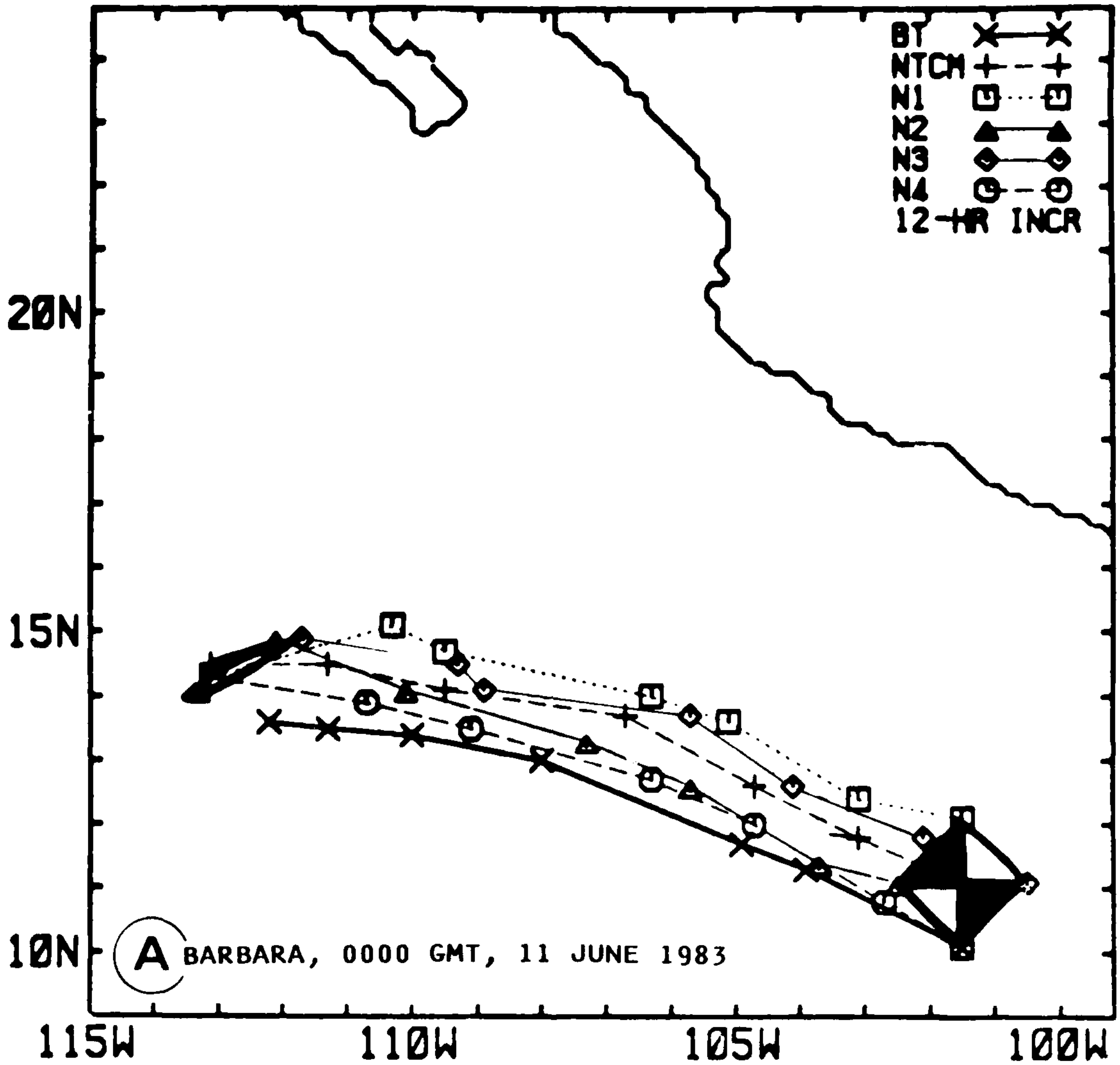

Figure 15. Two EASTPAC cases from the initial position sensitivity experiment. NTCM is NTCM2.0 and N1-N4 are the perturbed runs.

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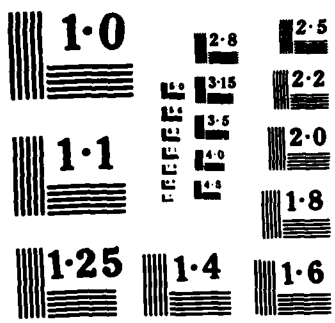


NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

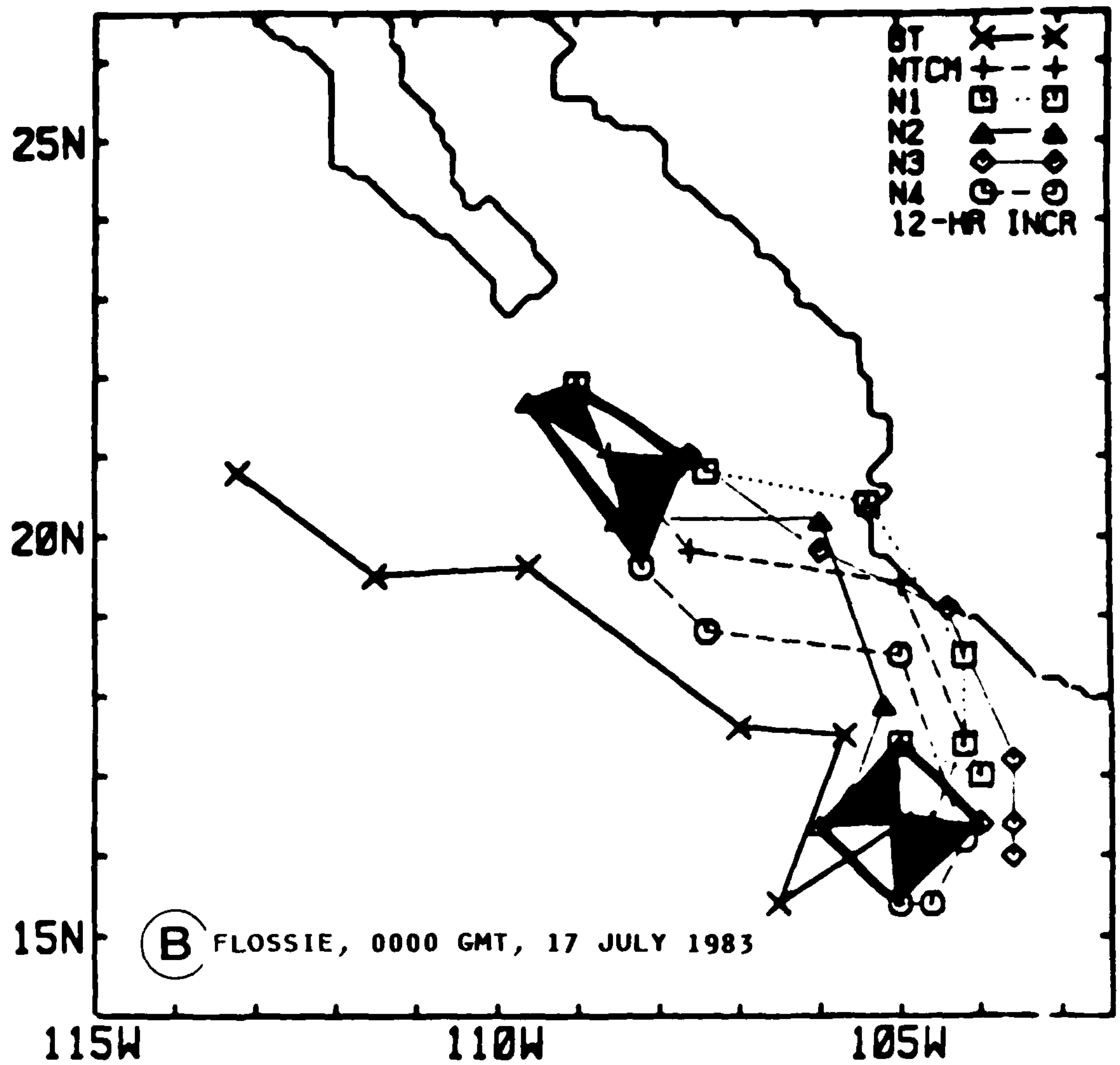


Figure 15, continued.

3.6 PREDICTABILITY

The sensitivity tests demonstrated that model physics could change model performance by 10-20% and that the choice of analysis (refer to the NTCM-MFM comparison in Sec. 3.2) could cause even greater variability (20-30%). A more important question was to what extent this variability could be exploited to improve model forecasts. The twin-experiment approach was used to assess the predictability limit of NTCM2.0 (Fiorino and Harrison, 1981).

Two simulations were made from the same operational analysis, but with the initial fields smoothed in two different ways. The difference in the fields was designed to be on the order of the "analysis" error, or that error due to how the analysis "fills in" the area between observation points. The two initial fields would be observationally indistinguishable from each other, but the difference would lead to changes in the model track forecasts. The amount of data was assumed to represent what is currently available and the study would not necessarily be valid if a large new data source was available. The predictability study gave some indication of what could be accomplished with today's resources.

Twenty cases were chosen and the model (NTCM2.0) was integrated for 5-days. *The skill of the "twins" was comparable, but the* net difference between the two tracks grew in time to nearly 250 n mi at 5 days. Combined with the uncertainties in locating the tropical cyclone, we estimated that the skill limits of NTCM2.0 are 105, 152 and 200 n mi at 24, 48 and 72 h, respectively. It appears that the NTCM, and other dynamic models, have a long way to go before reaching the predictability limit, regardless of the current data limitations.

3.7 NOGAPS VERSUS THE TROPICAL ANALYSIS

NOGAPS became the operational large-scale atmospheric forecaset model at FNOC in the summer of 1982. It was assumed that the global model analysis would be superior to the FNOC tropical Numerical Variational Analysis (NVA). A comparison of the NTCM2.0 forecasts using the NOGAPS analysis versus the NVA was made during the 1982 season. Although NOGAPS has been updated, it is believed that the 1982 results are still relevant. Fig. 16 displays the median forecast errors for this comparison. It is clear that NTCM performance with the NVA is far superior to that with the NOGAPS analysis.

FNOC TROPICAL ANALYSIS VS. NOGAPS

WESTPAC 1982

SIDE-BY-SIDE

MEDIAN FORECAST ERROR (NM)

	24	48	72
NVA	106	186	288
NOGAPS	131	264	342
CASES	263	217	176

Figure 16. Median forecast errors from the NOGAPS - NVA comparison in 1982. NVA is the Numerical Variational Analysis run at FNOC for tropical applications.

The greatest differences in the two wind analyses occurred in the tropics (20N to 20S), whereas the midlatitude flows were nearly identical. The NOGAPS analysis often disagreed with observed wind direction in the tropics by as much as 180°. We also observed reduced meridional winds and greater zonal flow in the tropics in the NOGAPS analysis. The NOGAPS initialization procedure is thought to be the cause of these discrepancies. Whatever the cause, the tropical analysis was again shown to be very important to model skill.

3.8 ATLANTIC APPLICATION

We continued experimentation in the LANT after the NTCM-MFM comparison. Because 4th-order diffusion gave superior results in sensitivity tests, the model was run with this feature on all cases in 1981. Fig. 17 compares the forecasts of NTCM2.0 (again called NTCM 82 in the figure) with those of the National Hurricane Center (NHC). As in WESTPAC, the "cross-over" point was around 48 h, or that the dynamic model showed better skill vis-a-vis the official forecast after 48 h.

The comparison of the model to the official forecast characterizes the model's guidance potential. The meteorological potential is better represented by improvements over a "no skill" aid. Neumann and Pelissier (1981) advocate a CLImatology-PERsistence (CLIPER) statistical model as the basis for normalizing cases with different characteristics. CLIPER models are now available for WESTPAC, as well as EASTPAC and the LANT. I will compare the operational NTCM forecasts in 1984 with these CLIPERs at the Project Meeting, but the 1981 results were still encouraging. We also verified these NTCM forecasts at NHC using their verification procedures. It was found that the NTCM was superior to CLIPER, although the results were not statistical significance for this small sample. Few storms occurred in the LANT during the 1982 and 1983 season and it has been impossible to compile a more comprehensive set of statistics on an operational basis.

3.9 COMPARISON WITH THE JAPANESE NESTED MODEL

The Japanese Meteorological Agency (JMA) has been running a nested-grid model similar to the NTCM (see comparison in Fig. 2) for a number of years. The Moving Nested-Grid model (MNG) has been making operational forecasts of storms threatening Japan since 1982. We have been comparing the NTCM to the MNG for the last three years and have found that the Japanese model is generally better

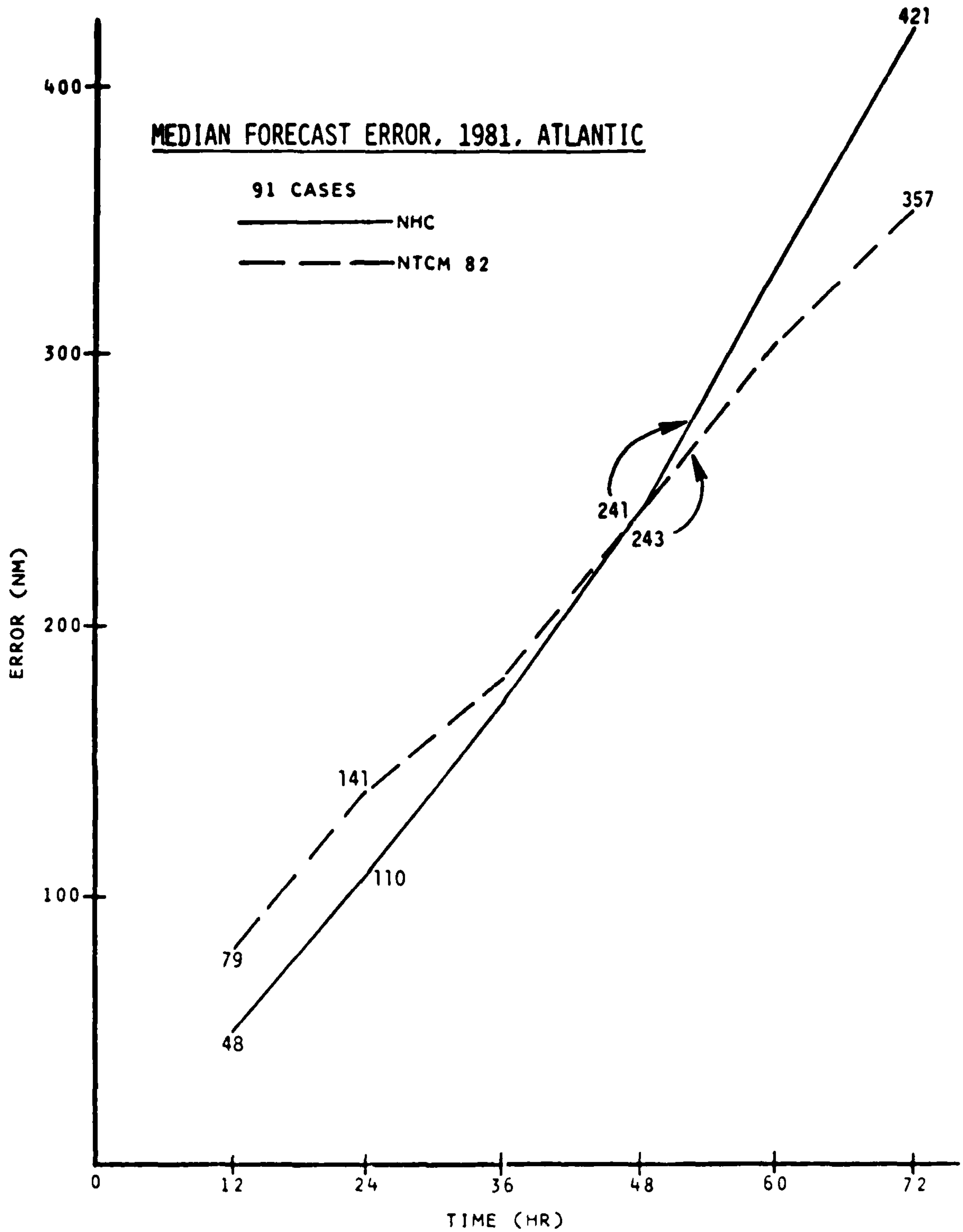


Figure 17. Median forecast errors for the 1981 LANT hurricane season. NHC denotes the official forecasts of the National Hurricane Center and NTCM82 is NTCM2.0.

than the NTCM in the midlatitudes, whereas the reverse is true in the tropics. Fig. 18 shows two representative cases from the 1982 season. The operational MNG forecast takes IRVING too far to the north compared to the NTCM for this tropical case (panel A). The NTCM missed the recurvature of JUDY while the MNG made a very good forecast (Panel B) The MNG track drawn with boxes (3L-R83) is the 1983 model. The analysis procedures of FNOC and JMA treat the tropics differently and we reasoned that the FNOC analysis may be beneficial for storms in tropical regions.

3.10 PERSISTENCE ADDITION BY THE BIAS CORRECTOR

One important difference between the NTCM and the MNG is that the MNG uses the "bias corrector" of Shewchuk and Elsberry (1978). Ookochi (personal communication) of JMA has found that the bias corrector lowers the 24 and 48 h mean forecast errors of the MNG. As noted earlier, OTCM skill, particularly at short-range forecast intervals, has been significantly improved by the persistence-addition property of the bias corrector. Thus, there was justification to test the bias corrector in the NTCM.

The principle behind the bias corrector is very simple. If the model *storm's initial motion over a 6 to 12 h period deviates from the* observed *motion* before the time of integration, then restart the model with a modified wind field around the storm that will "blow the storm back on course." The purpose of the bias corrector is really two-fold: 1) to "correct" the analysis so that it produces a track which is consistent with current storm behavior; and 2) to compensate for model deficiencies and initialization errors that can cause the storm to initially "wobble" off course. We cannot tell before hand which problem is dominant, i.e., whether we are really "fixing" the analysis or the model.

The first step in the NTCM bias corrector is to integrate the model for 12 h and compare the model motion to the storm motion in the -12 to 0 h time period. By contrast, JMA integrates the MNG for 6 h and compares the 6 h model position to the observed +6 h position. This is possible because the MNG does not begin the forecast integration until about +8 h after synoptic time. Thus, the new 6 h warning position is available to use in the bias correction. The OTCM bias corrector is similar to the NTCM's, except for a 6 versus 12 h integration. The 12 h integration of the NTCM provides a more representative initial motion.

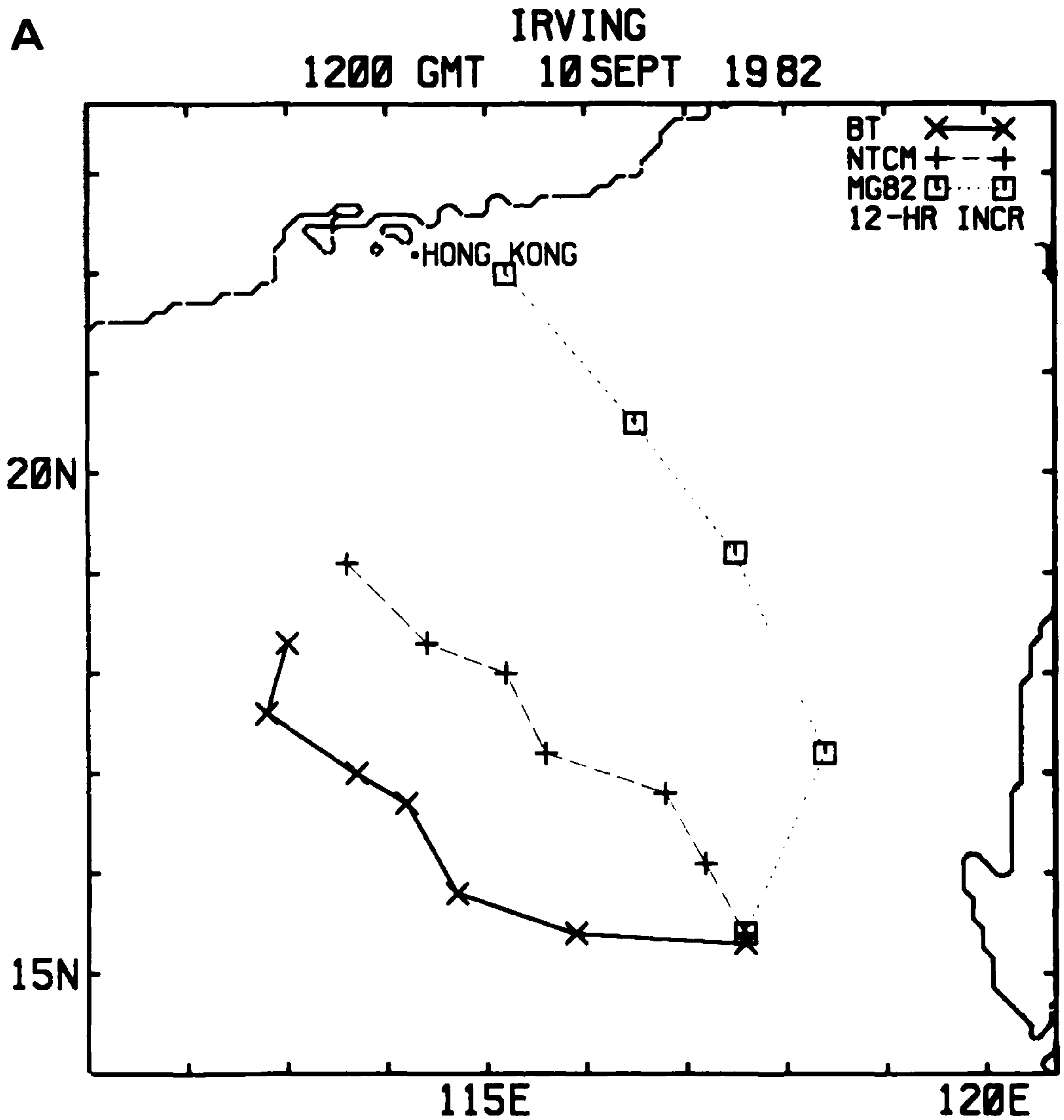


Figure 18. Two cases from 1982 WESTPAC season comparing performance of NTCM1.2 (NTCM in figure) to 1982 (MG82) and 1983 (MG83) versions of the MNG of JMA.

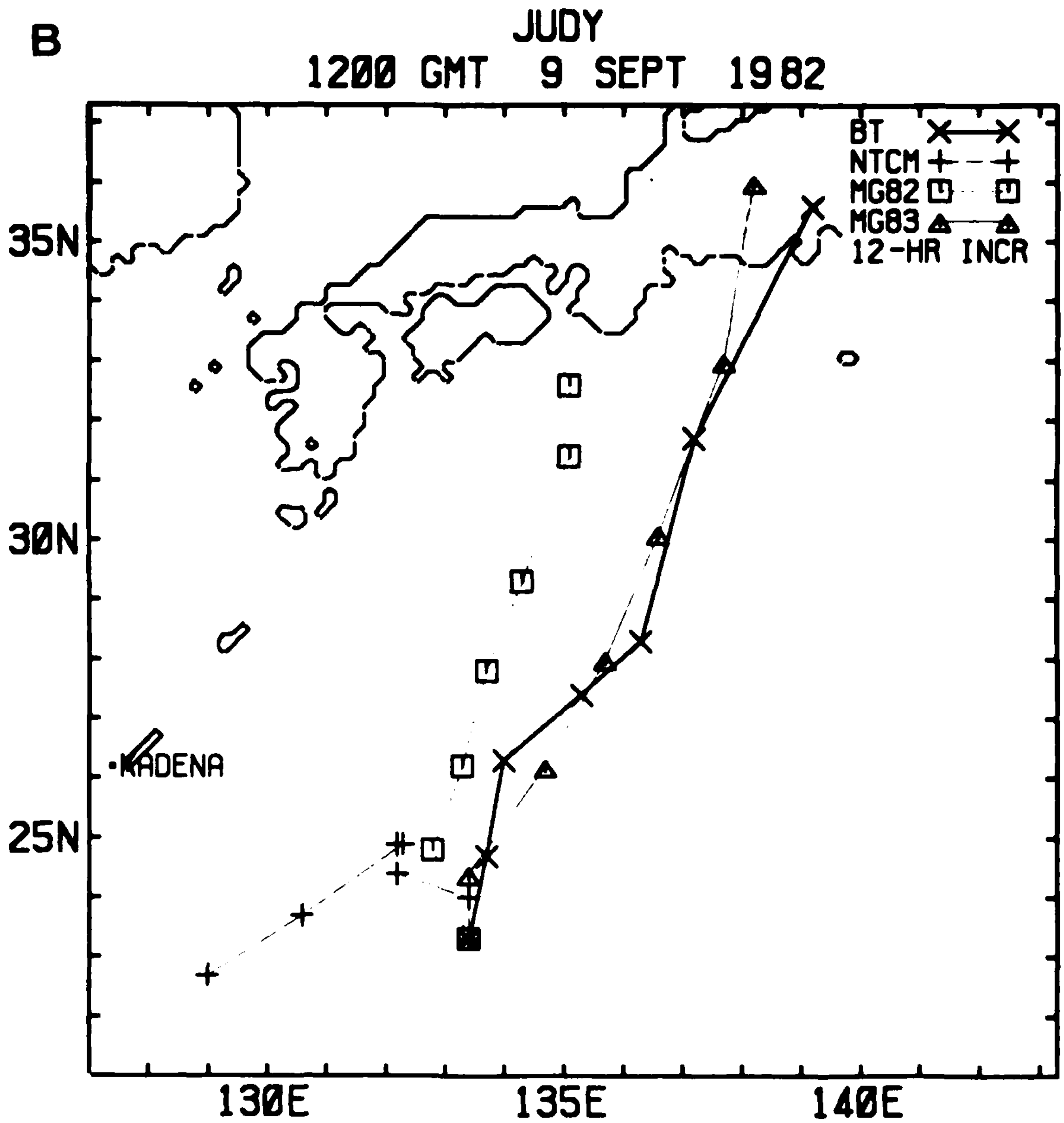


Figure 18, continued.

The second step is to calculate the wind correction factor, which is simply the vector difference between the observed and model motion. For example, if the model-predicted motion was 270 deg at 10 knots and the storm was moving at 270 deg and 20 knots, the wind correction would be toward 270 deg at 10 knots, or an easterly wind. If linear advection was the only motion process in the model, then adding the easterly wind of 10 knots in the region of the storm would adjust the model storm to the observed speed. Some experimentation is necessary to determine the fraction of the wind correction factor that should be applied, and the vertical and horizontal domain over which the correction should be made.

We initially chose 30 cases from the 1983 season that had very large errors at 24 h (worst case situations) to develop the wind correction distribution. The first approach was similar to the Japanese scheme which uses a full correction (addition of the wind factor to the existing winds) within 615 km (three coarse grid points) of the storm and then a linearly decreasing correction from 615 km to 1030 km. Further, this correction was applied equally at all levels. The forecast errors were dramatically lowered (30-50%) at all forecast intervals. We had obviously chosen cases where persistence was an important factor in the observed motion and the forecast. These initial tests provided a "bound" on the improvement possible by the bias corrector.

A more representative set of cases was selected from the 1982 season by a Typhoon Duty Officer (TDO) from JTWC. This set consisted of 107 "meteorologically independent" cases (36 h separation between cases for a given storm). They contained a typical mix of tropical cyclone motion types, e.g., loopers, stallers, straight runners, etc. The overall sample size was later increased to 157 with the addition of 50 independent cases from the 1983 season which were again selected by the TDO. The JMA-type wind correction distribution resulted in smaller forecast errors at 24 and 48 h in 1982, although the improvement was not as great as in the 30 "worse-case" sample discussed above. However, the 72 h forecast error was <u>degraded</u> by 13%. This degradation was as large as the variations found in physical parameters sensitivity test. Therefore, it would have been very difficult to compensate by simply "tuning" the model. An alternative was to try different distribution functions. We found that applying the correction only in the lowest layers gave the best results in the sense that the

results in the sense that the 72 h skill was minimally affected while retaining the improvements at 24 and 48. We concluded that the bias corrector led to a slight, but noticeable degradation in the long-term skill of NTCM2.0.

We looked for a relationship between bias correction improvements and the discrepancy between the model and observed motion, i.e. if the model deviated at large angles and speeds from the actual storm motion, the bias corrector would be advantageous, even at 72 h. Unfortunately, there were more instances where the bias corrector had a negative effect on the forecast (out to 72 h) than a positive one, even for these extreme cases.

It might be argued that the number of cases was insufficient to make definitive conclusions and that there may have better ways to apply the corrector. Although these criticisms may be valid, our testing, in terms of cases and distribution functions, was far more extensive than in the original development (Shewchuk and Elsberry, 1978), or in the OTCM, and MNG tests. Nevertheless, the bias corrector merits further evaluation.

3.11 PERSISTENCE ADDITION BY POST-PROCESSING

The bias corrector is a pre-processing technique. That is, the correction is made <u>before</u> the final forecast model integration. Alternately, the forecast could be post-processed by statistically and/or dynamically adjusting the forecast track <u>after</u> the integration. Peak and Elsberry (1984) applied a statistical technique to NTCM1.2 forecasts in the Southern Hemisphere (SHEM) with a good deal of success. A more dynamical approach was developed by Allen (1984). His method is to first make a 72 h position forecast. The 24 and 48 h positions are derived from a linear combination of a pure persistence forecast and a line drawn from the initial position to the 72 h forecast. The 24 h forecast is heavily weighted toward persistence, the 48-h contains more of the 72 h forecast and the 72 h forecast is unchanged. The success of Allen's strategy depends on the quality of the 72 h forecast. If the long-term prediction is good, then the persistence-type assumption should work very well in "filling in" the remainder of the track. I view his post-processing method as dynamical because the adjustment uses the dynamical idea of inertia or motion persistence.

We tested an approach similar to the Allen post-processing technique with the unbiased (no bias corrector) 72 h NTCM prediction -- unbiased because this version had the best 72 h skill for the 157-case sample. An estimate of persistence factor was derived from the JTWC "working best track" which is used by all the forecast aids run at FNOC. This track gives the best motion estimate that is available in an operational environment.

The results are summarized in Fig. 19. Three versions of the model are compared: 1) no persistence addition (NTCM2.0); 2) pre-processing persistence addition (bias corrector); and 3) post-processing persistence addition (what will be called NTCM2.1). The bias corrector degraded 72 h performance, but improved the 12 and 24 h skill. More importantly, post-processing was superior to pre-processing because the long-term skill of the "pure" model was retained.

This result is another confirmation of my contention that the model 24 and 72 h forecast position may be "disconnected." The positions are connected physically, but in the model world the connection is "blurred" beyond recognition. Conceptually the model can be thought of as making two types of forecasts -- a long-term track (72 h long) with large-amplitude oscillations (12-24 h or even longer) about the long-term track. These "jogs" are often times related to initialization and model noise and are probably not meaningful. More importantly, they may confuse the forecaster. Allen's post-processing technique acts as a track smoother by eliminating the track "noise" while leaving the "good" long-term track unchanged. Fig. 20 shows three cases with an increasing time scale in the oscillations of the raw NTCM track about the post-processed track. The ODESSA (Panel A) oscillations are on the order of 6 to 24 h, while IRVING's "noise" track (Panel C) has a much longer time scale. The post-processed version of NTCM2.0 was run routinely at FNOC in 1984 and will be referred to as NTCM2.1.

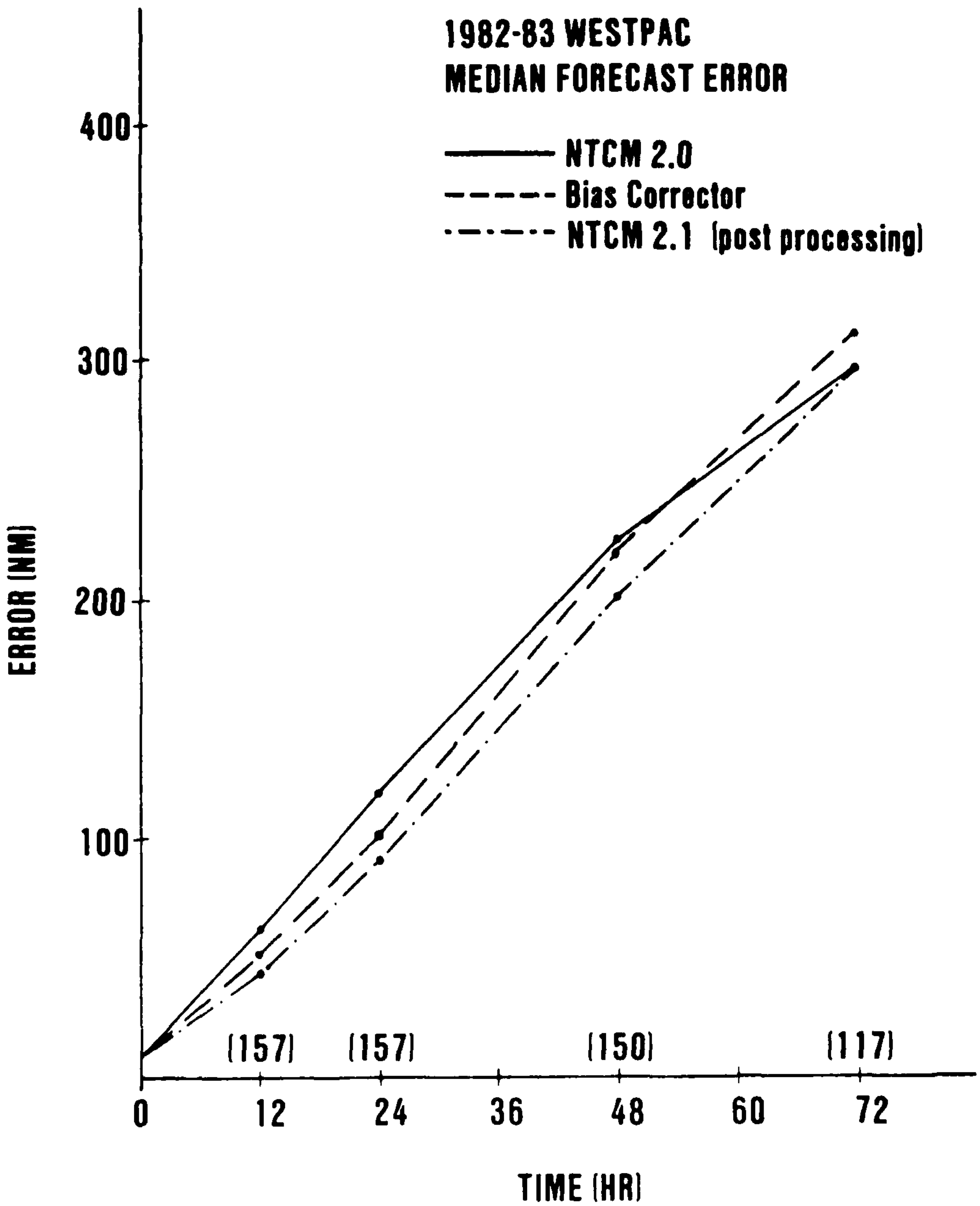


Figure 19. Median forecast error from the persistence addition tests. The cases were chosen by JTWC to represent a typical assortment of storm types.

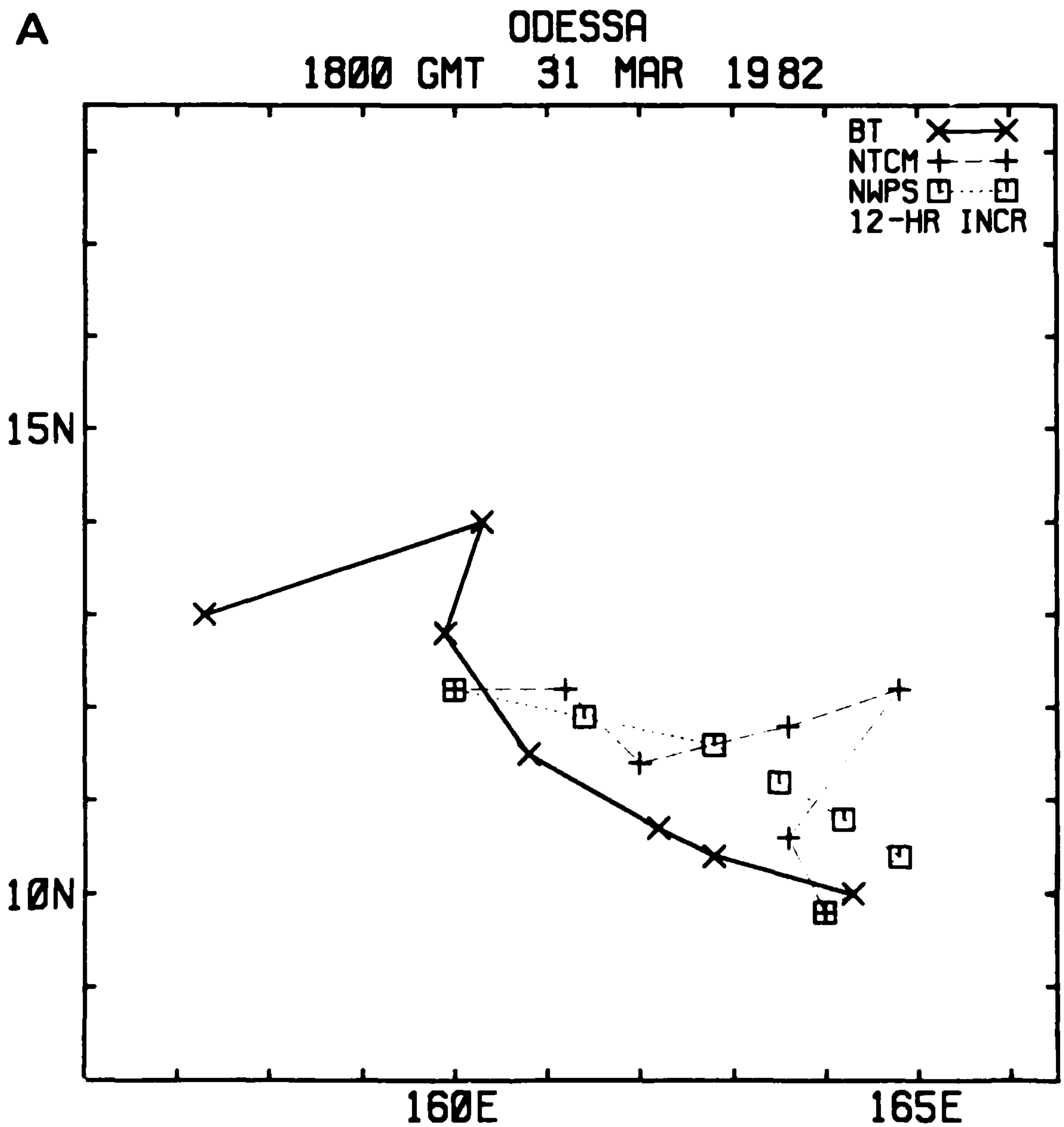


Figure 20. Three cases from 1982 WESTPAC season illustrating post-processing technique. NTCM stands for NTCM2.0 and NWPS refers to NTCM2.1 (the same as NTCM2.0 except for the persistence post-processing).

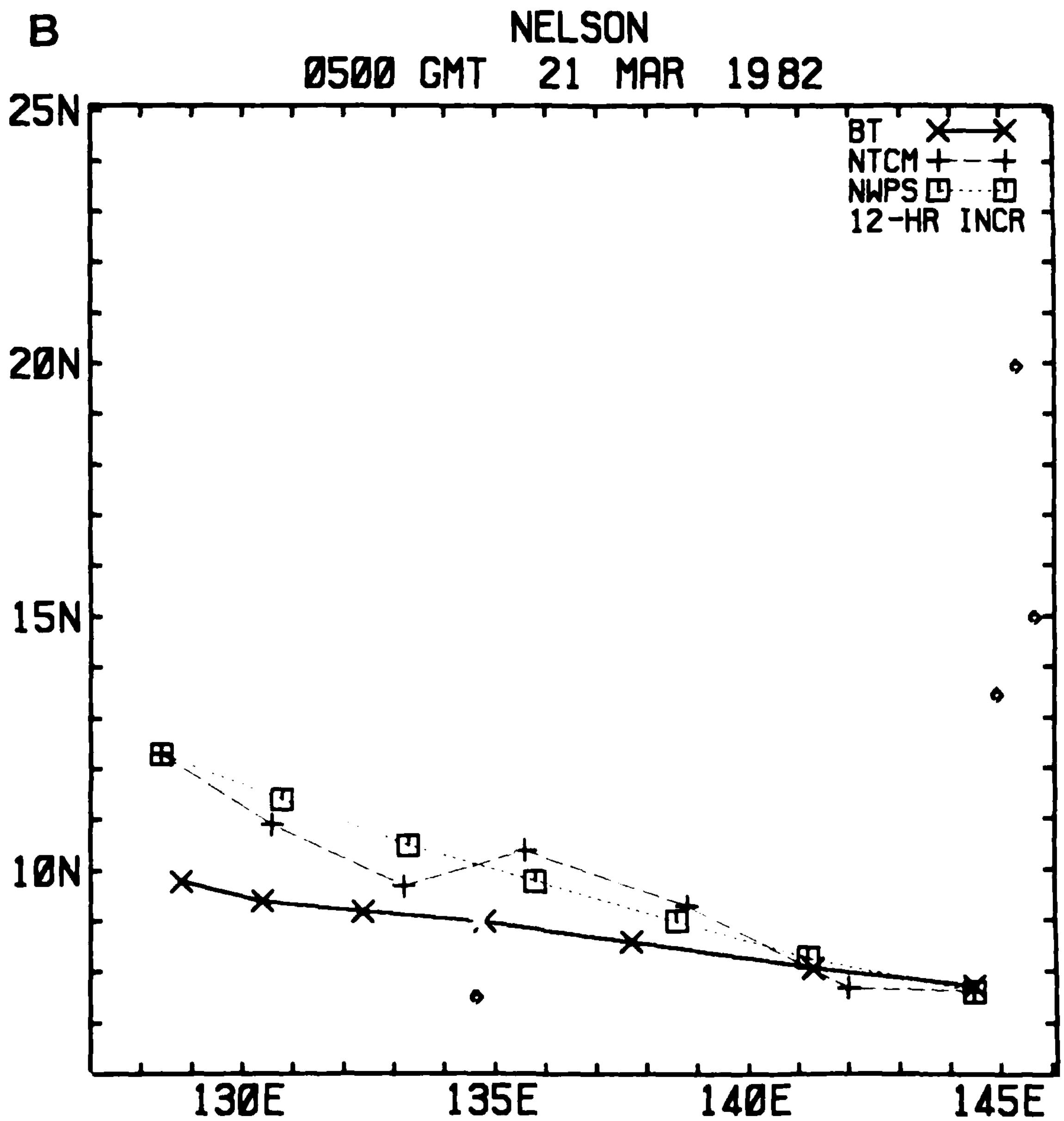


Figure 20, continued.

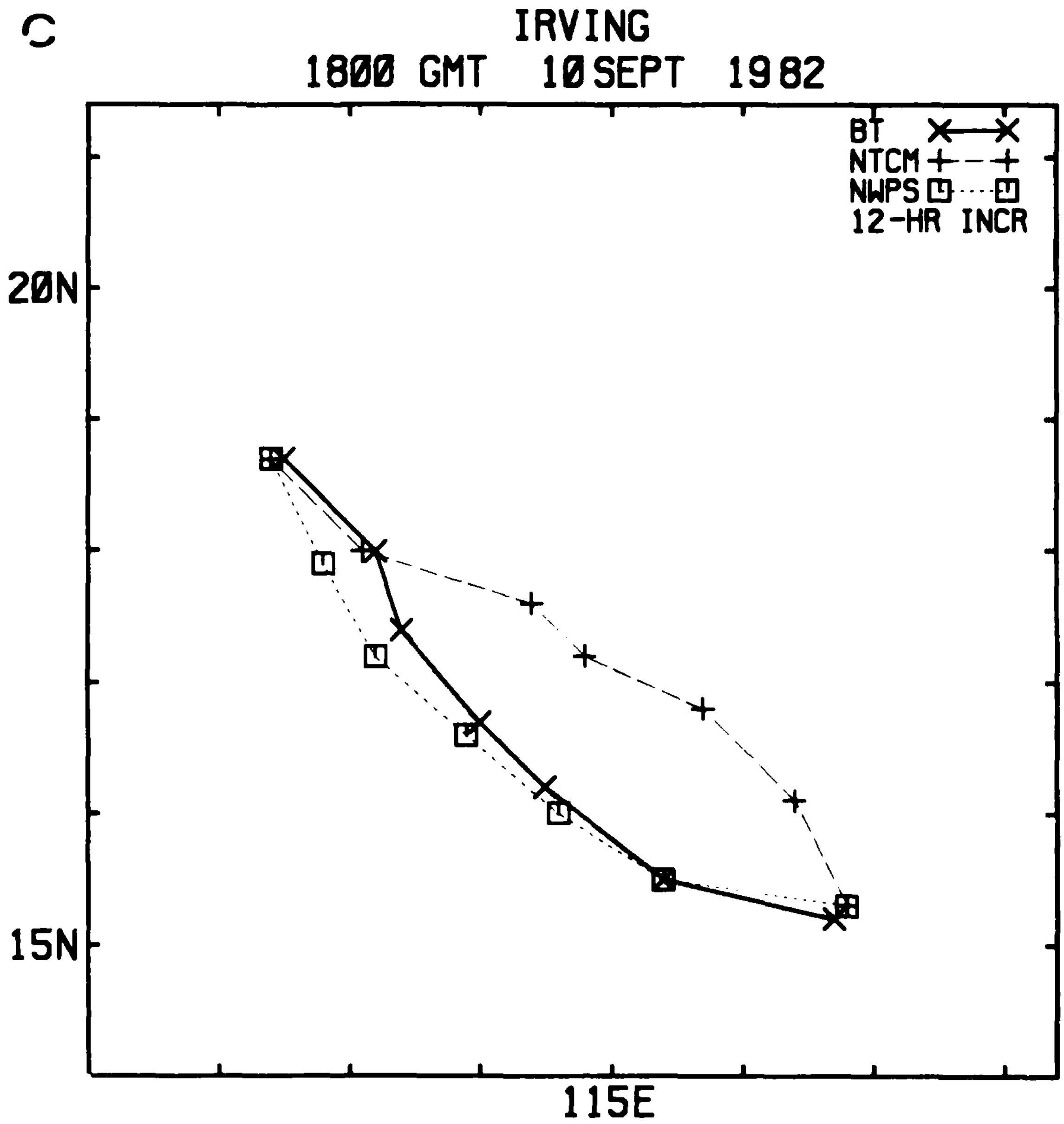


Figure 20, continued.

3.12 SUMMARY

Before I discuss the operational results of NTCM2.0 and NTCM2.1, I will summarize the findings from the testing of NTCM2.0:

1) The physical parameters that control vortex evolution and structure (the analytic heating function and momentum diffusion) have the greatest impact on the model's long-term skill.

2) Changes in the large-scale analysis that initializes the model causes the greatest overall changes in performance.

3) Model skill at 24 h is not closely connected with 72 h skill.

4) Post-processing persistence addition is superior to the pre-processing bias corrector.

4.0 OPERATIONAL EXPERIENCE WITH NTCM2.0

Harrison's tests with offsetting the time of the position and the analysis (refer to Section 3.3) became the basis of the 1983 operational schedule shown in Fig. 21. The 1983 schedule was designed to get the NTCM forecast to the centers before the warning was issued. For example, the 00 GMT warning is issued at 03 to 04 GMT, and the NTCM track from the 00 GMT position would be run at 02 GMT. Short delays in computer scheduling have a minimal effect because the model takes only 50 sec CPU time on the CYBER 205. Notice that the 18 GMT and the 00 GMT forecasts are based on the previous 12 GMT analysis, whereas the 06 GMT and 12 GMT forecasts are based on the previous 00 GMT analysis. The 1984 (current) schedule is somewhat different from the one in Fig. 21. The change was made so that all JTWC forecast aids would arrive on Guam at roughly the same time. The time offsetting is still used, however.

4.1 1983 WORLD-WIDE PERFORMANCE

The 1983 NTCM error statistics by basin are given in Fig. 22. Individual storms statistics are also plotted to give a sense of the spread in skill. The NTCM was run on all tropical cyclones regardless of intensity (20 kt and greater). We have not stratified forecast error according to maximum wind, although this work is now underway at the Naval Postgraduate School (NPS). The model forecast was verified against the warning track, again regardless of intensity. Warning track comparison is similar to best track verification for the long-term forecasts only. The 24 h errors are slightly lower when the best track is used.

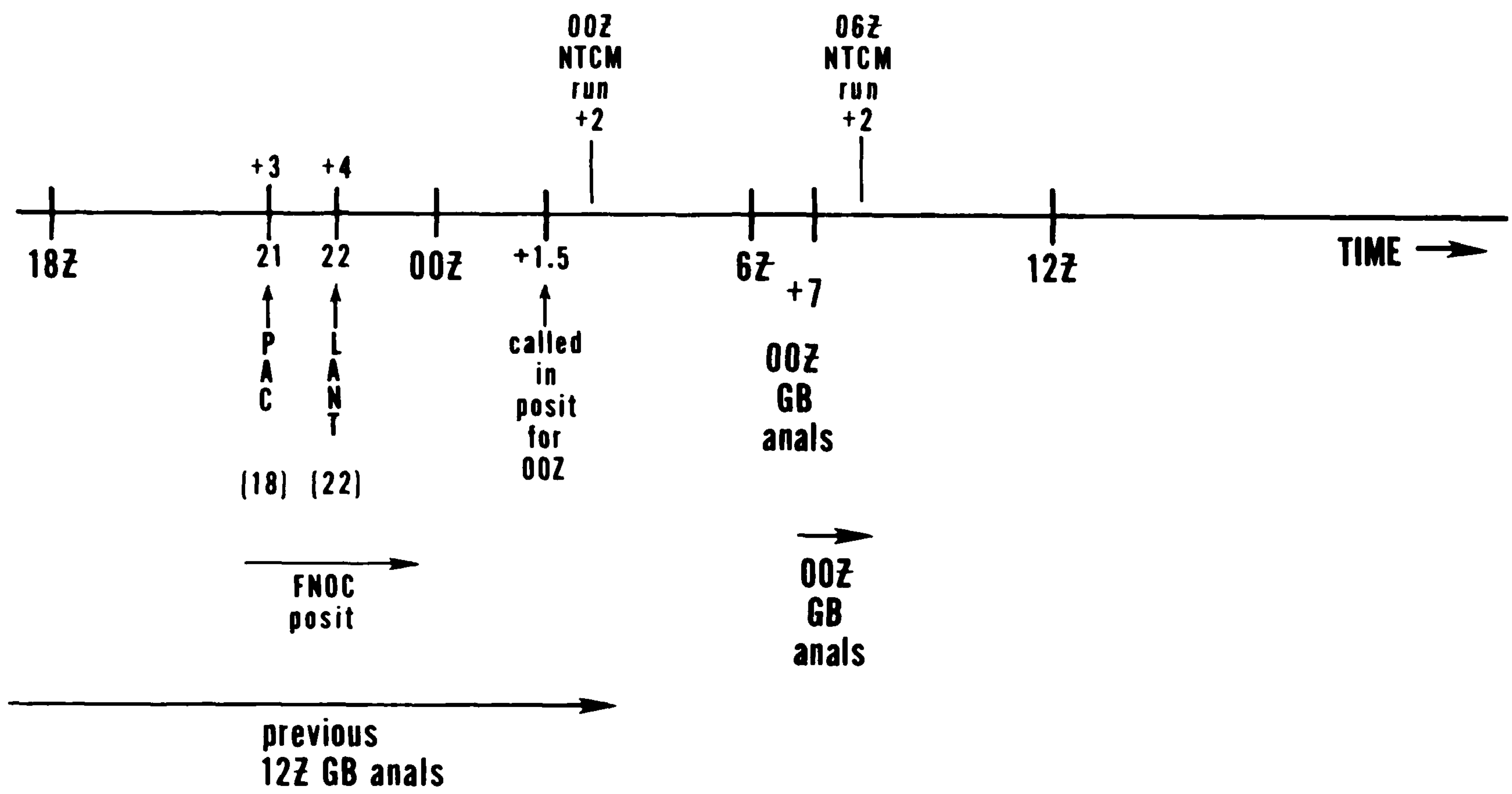


Figure 21. The 1983 NTCM operational schedule.

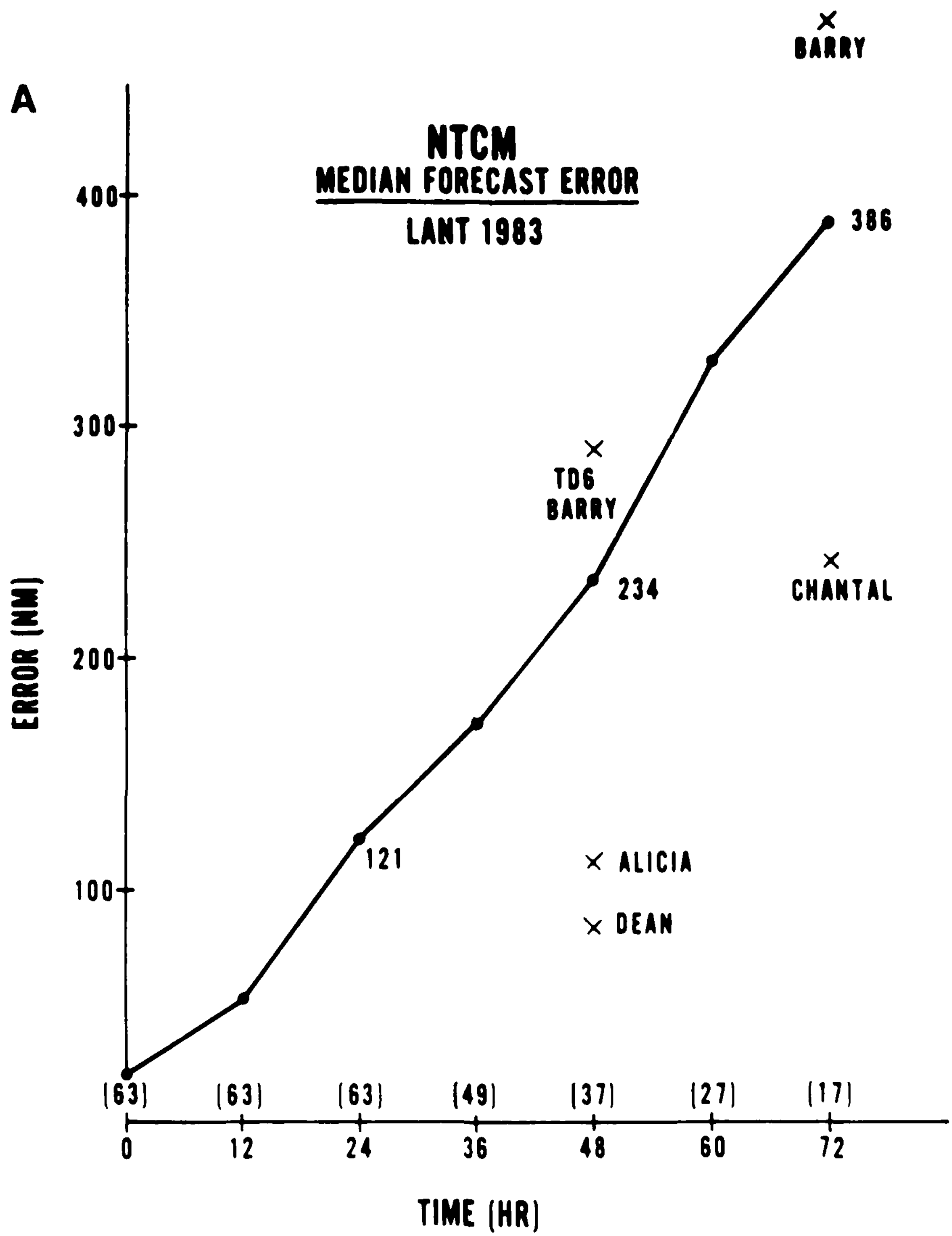


Figure 22. The operational results from the 1983-84 tropical cyclone season. The statistics are stratified by basin.

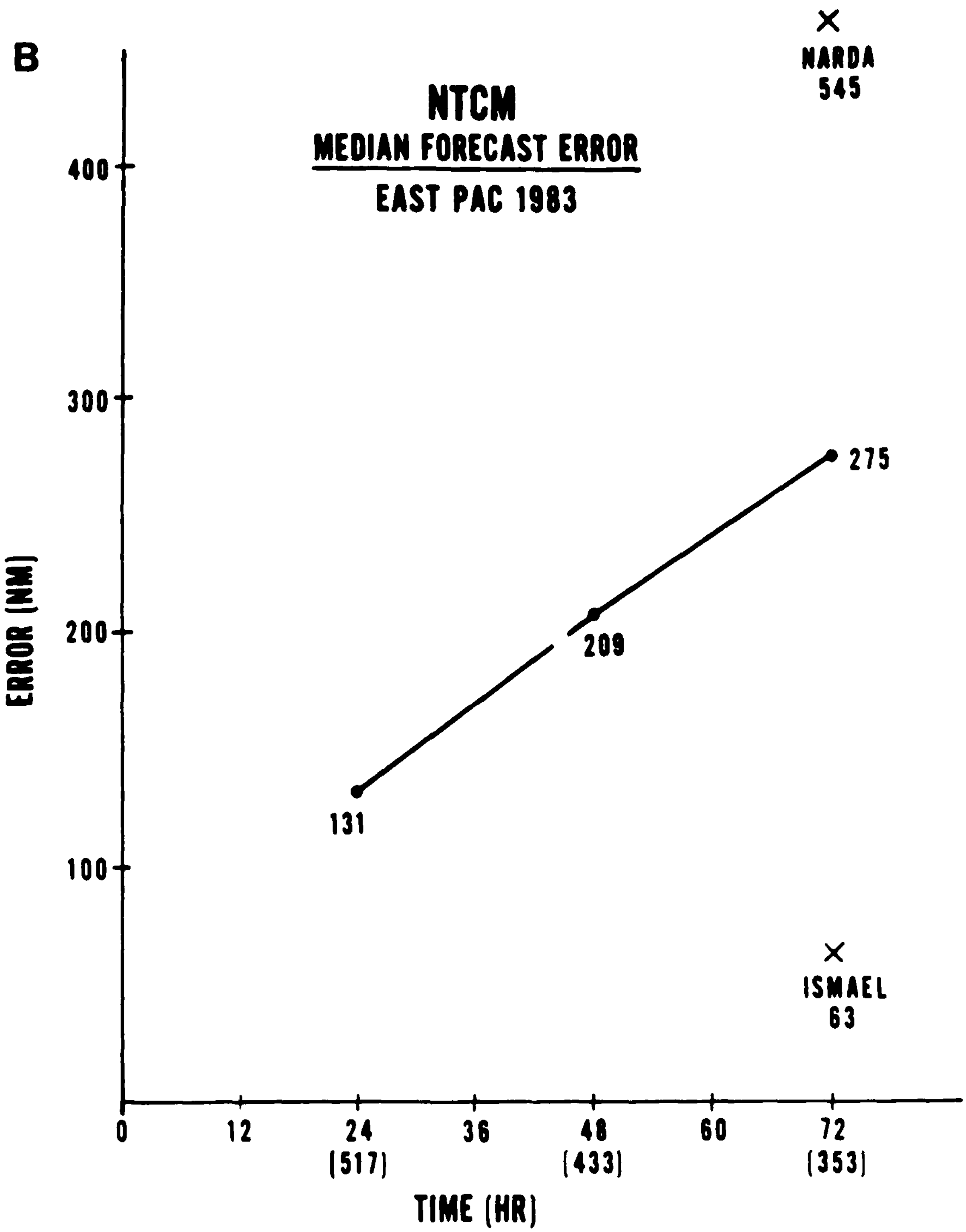


Figure 22, continued.

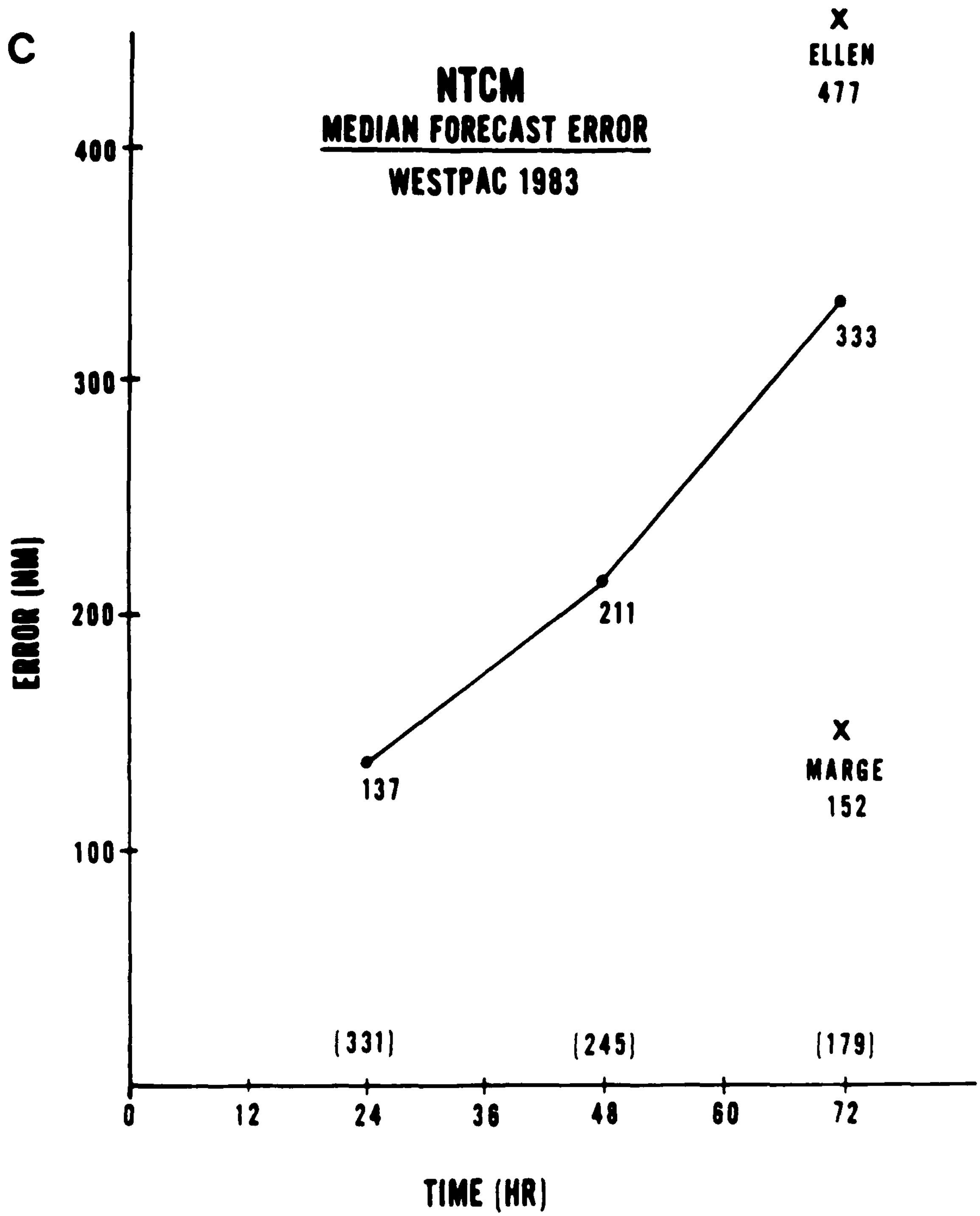


Figure 22, continued.

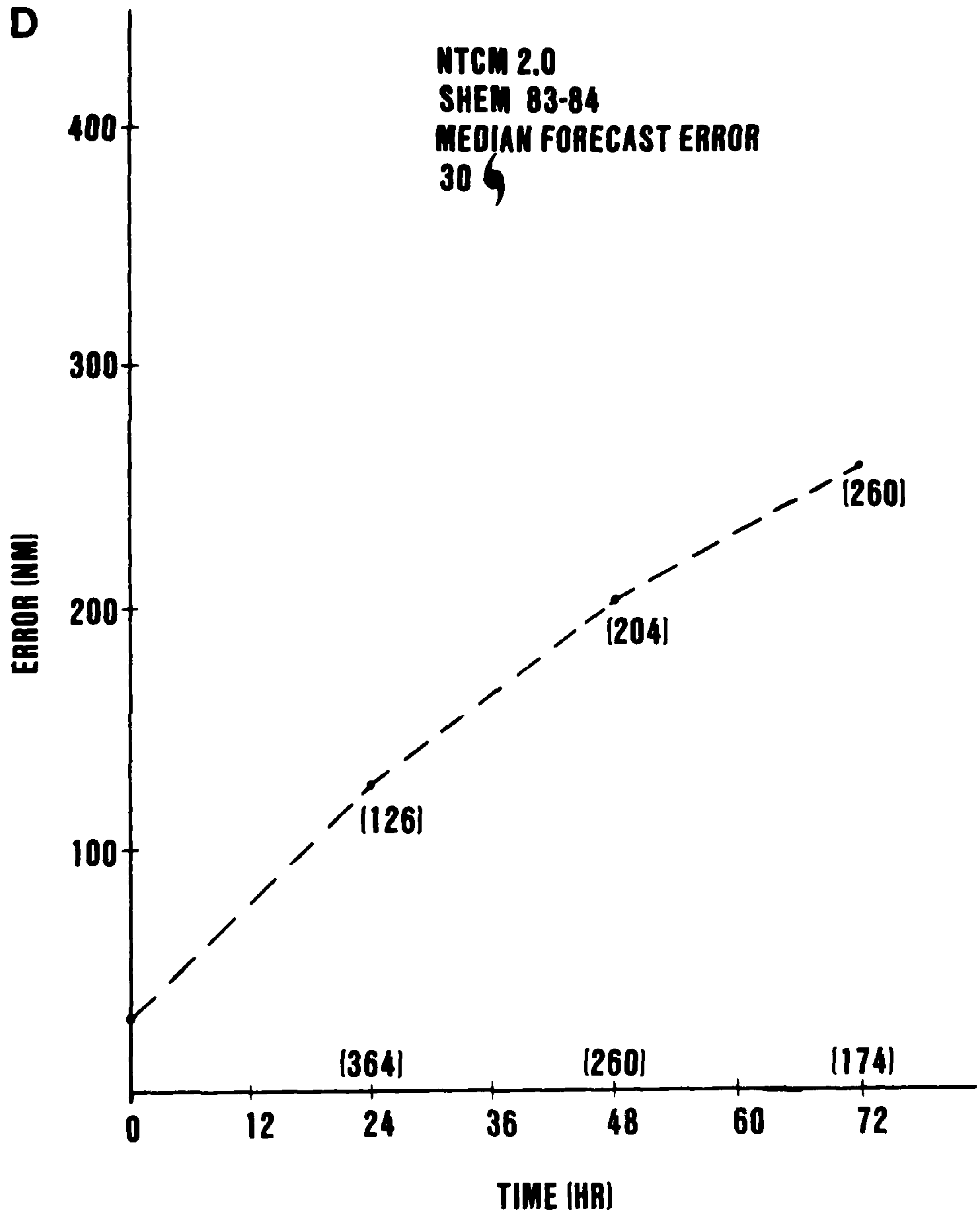


Figure 22, continued.

The graphs show how forecast error varies considerably from one basin to the next, with the poorest performance in the LANT. The errors in SHEM and EASTPAC were lower than expected, based on the quantity of data available in these regions. Several explanations are possible. The FNOC tropical analysis reverts to climatology in the absence of observations. If the large-scale flow did not depart too far from climatology, then the analysis used by the NTCM would have been fairly accurate. Our experience also suggests that the NTCM does not handle all meteorological environments with equal skill. The storms in EASTPAC and SHEM may have been optimal for the model in the mean. There were, however, many individual cases where the model had great difficulty. In fact, the greatest spread in skill was found in the basins with the best net forecast errors! Even though there was variation in the forecast errors between basins, we cannot say whether the meteorological skill of the model was different. Only a comparison with a no-skill aid such as CLIPER can distinguish true skill.

4.2 EFFECT OF THE TIME OFFSET

We stratified the errors in WESTPAC according to forecast time to determine how the time offsetting affected median forecast error (Fig. 23). The number of cases at 00 GMT/12 GMT is nearly identical to the number at 06 GMT/18 GMT, but the statistics were different. The percent increase in error from 06 GMT/18 GMT to 00 GMT/12 GMT is also displayed and we find a serious degradation in skill, on the order of 10%. The forecasters had been warned that the "on-time" NTCM runs might not be as good as the "off-time" forecasts. The results confirmed our suspicions and suggest that it might be best to run the dynamic models only once per analysis cycle.

We stratified the EASTPAC cases in the same manner, but did not find substantial changes. Several interpretations for this curious result are proposed. The relationship between the position of the storm and the environmental flow features is either less variable or of a larger scale in EASTPAC. That is, the synoptic forcing may be of such a large scale that a 60 to 100 n mi difference in storm location relative to the environment is inconsequential to the motion. This makes sense synoptically. In contrast to WESTPAC, there are no large land masses, and the associated baroclinic zones, to the west of the tropical cyclone formation region in EASTPAC. Another possibility is that the paucity of data in EASTPAC relative to WESTPAC leads to a wind analysis that is fairly steady and of a larger scale.

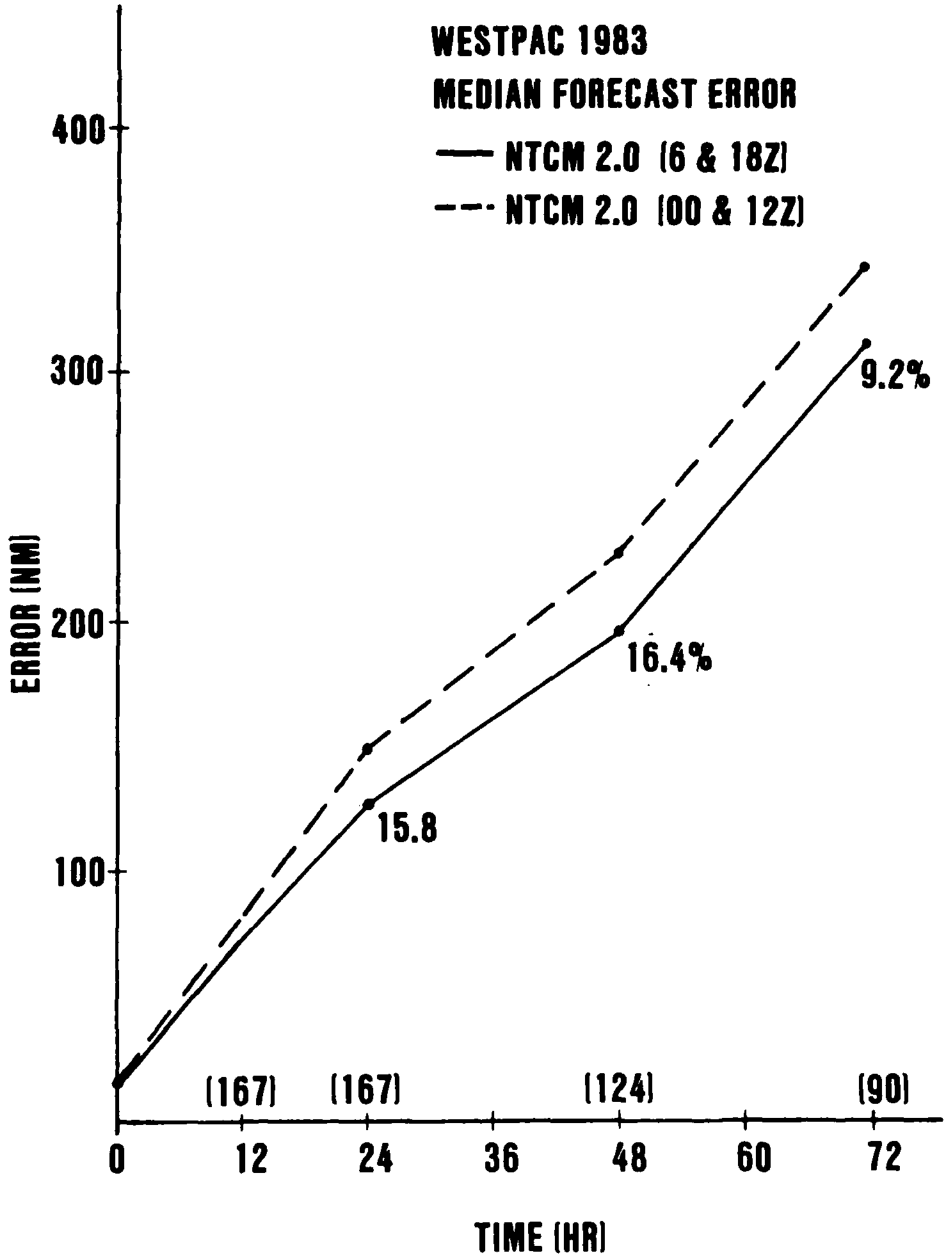


Figure 23. Median forecast error in the off-time (06 GMT and 18 GMT) versus on-time (00 GMT and 12 GMT) NTCM comparison from the 1983 WESTPAC season.

4.3 SUPERTYPHOON ABBY

The main intent of 1983 operational experiment was to increase the experience base of the NTCM. Much has been learned from this experience, especially from individual failures such as Supertyphoon ABBY of the WESTPAC. ABBY was not the first supertyphoon (maximum winds greater than or equal to 130 kt) of 1983, but ABBY had the largest impact on DOD assets. The track of ABBY, and a selection of NTCM forecasts, are displayed in Fig. 24. The model was consistently to the left of track while ABBY moved slowly northward before making landfall near Tokyo. The official forecasts followed a similar track and caused many DOD installations to prepare unnecessarily and resulted in the suspension or adjustment of several military operations. The other aids used by JTWC made the same type of error and it was the consistency among the aids that gave support to the JTWC forecasts.

Because of the concerns raised about ABBY, FNOC was tasked to explain the NTCM tracks. Our first suspicion was that the size of ABBY was a factor. Two lower tropospheric wind fields from the coarse grid of the NTCM are shown in Fig. 25. The fine grid (1200x1200 km) is indicated for comparison. At 06 GMT 7 August 1983, the circulation of ABBY was well contained within the inner grid. However, the storm circulation extends well beyond the fine grid at 06 GMT 12 August, 1983. The analytic heating function that maintains the model storm vorticity is not designed to simulate a tropical cyclone of ABBY's scale; nor is the inner grid large enough to provide the necessary resolution. Although we are not certain that the size of ABBY was the only problem, the large discrepancy between the model and reality had to be a contributing factor.

The NTCM was originally designed to handle a limited class of tropical cyclone systems, namely well-developed, vertically stacked storms of "typical" size. The model was run on all cases in 1983, including depressions because we had found that the NTCM could predict some depressions with skill. The ABBY case suggests we either have to adapt the dynamic model or not run it for the extreme situations. Another extreme case occurred in EASTPAC.

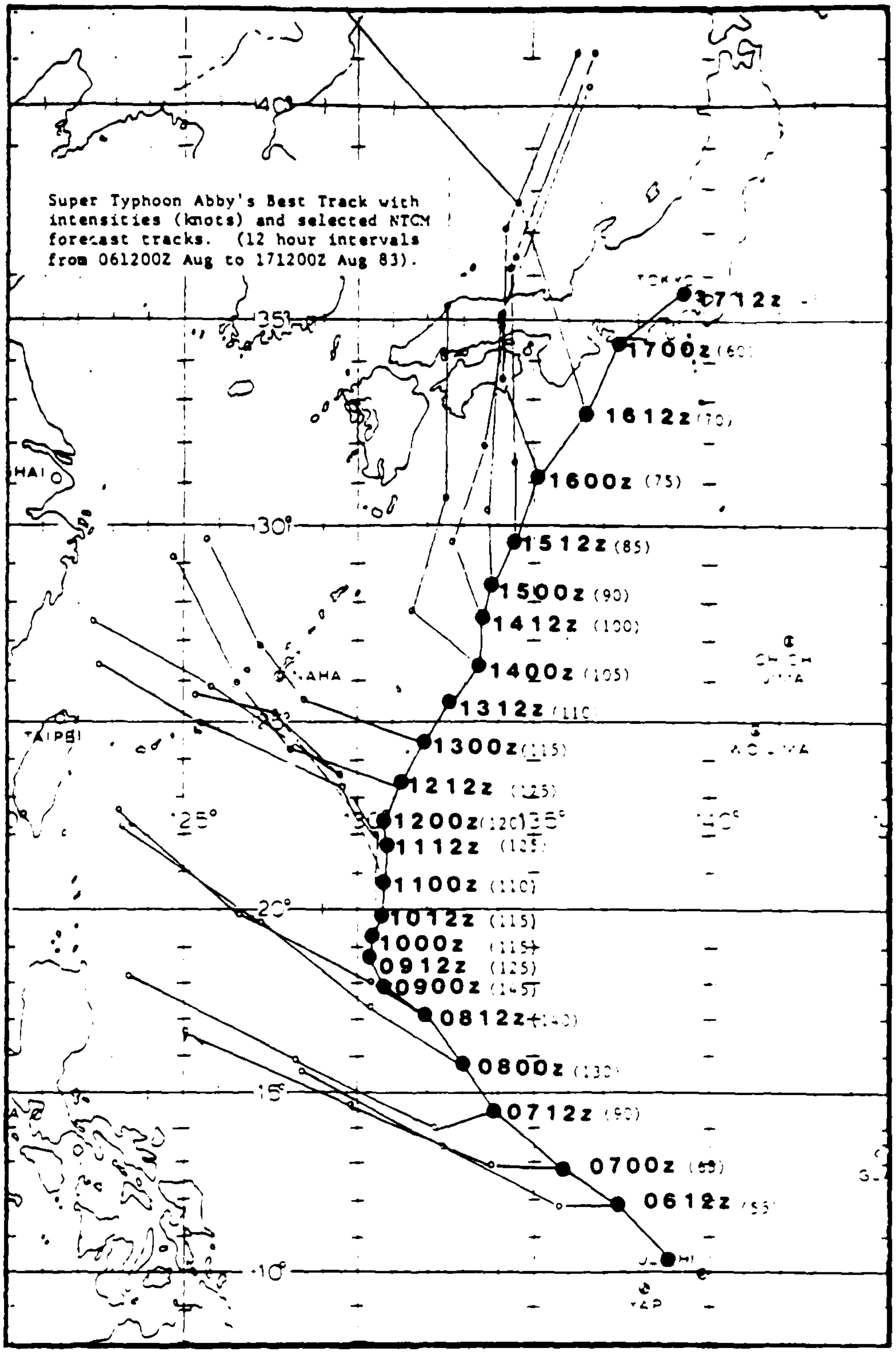


Figure 24. A selection of NTCM forecasts for Supertyphoon ABBY of 1983.

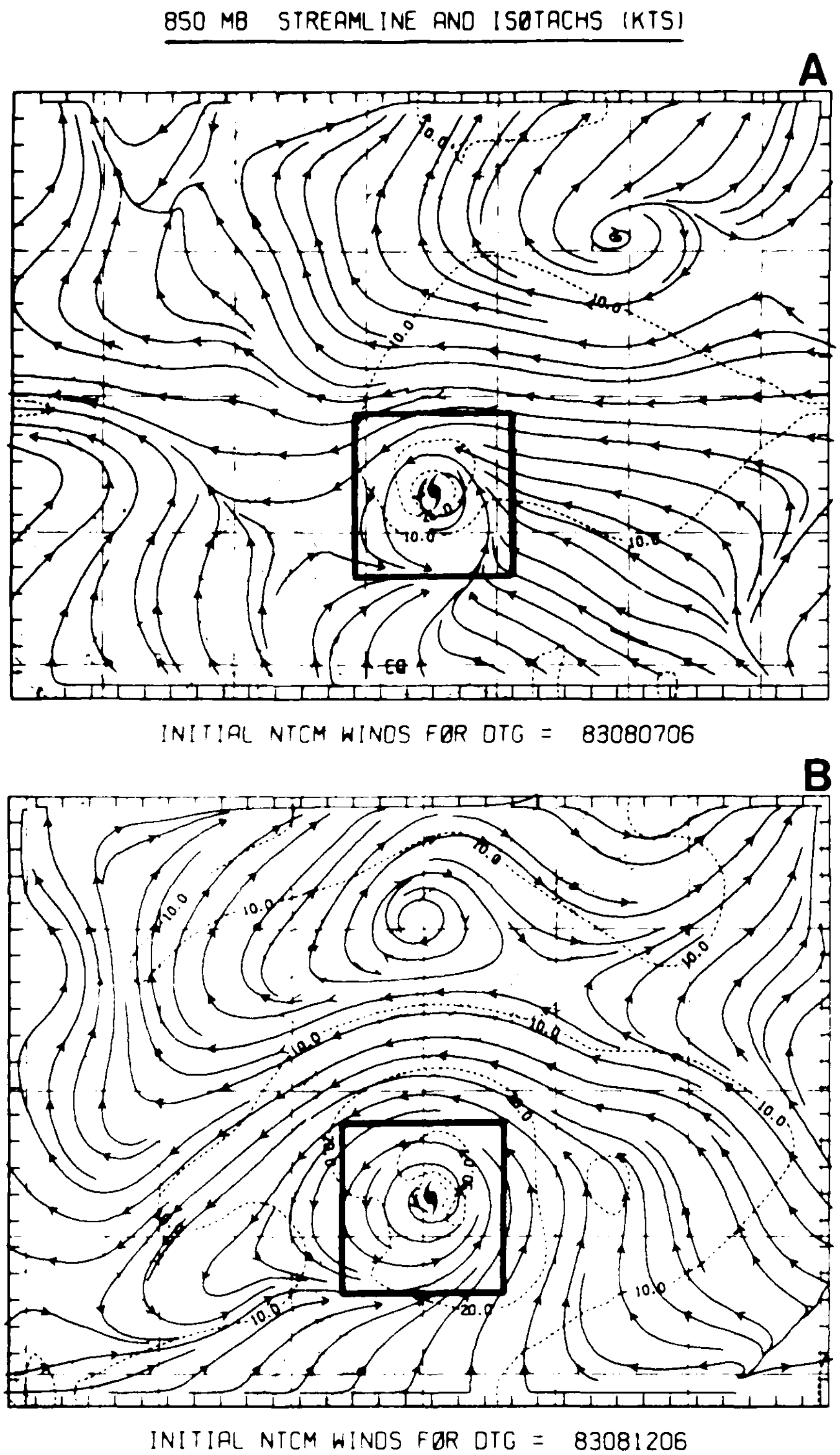


Figure 25. Streamline and isotach analyses of the 850 mb flow on the NTCM coarse grid for two times in the lifetime of ABBY. The perimeter of the inner grid is indicated for reference.

4.4 EASTPAC

The operational experiment in 1983 included the first model runs in EASTPAC. Fortunately, 1983 was a very active year and many types of storms occurred, ranging from intense, straight-running hurricanes to tropical storms recurving into Baja and southern California. The most striking observation, however, was the frequent occurrence of shallow, weak tropical storms and depressions. Again, the physics and dynamics of the NTCM were not intended to predict the track of weak and shallow systems. Tropical Storm NARDA clearly demonstrated this model deficiency.

4.5.1 TROPICAL STORM NARDA

NARDA travelled from the coast of Central America to beyond the Hawaiian Islands without reaching significant intensity. From satellite imagery, it appeared that the circulation was capped at about 700 mb during much of this period. The dominant synoptic forcing came from the northeasterly trades and the storm took a nearly straight westerly course. The model, on the other hand, consistently predicted a northward movement. Southerly flow was observed aloft over Hawaii as the storm approached the islands. The model heating field forces a deep tropospheric circulation which apparently allowed the southerlies to influence the motion of the vortex. Furthermore, the beta effect would have been greater because the model storm was more intense and larger than NARDA. Both influences were probably responsible for the incorrect forecast.

NARDA and ABBY highlight a model weakness related to vortex specification and maintenance processes that needs to be addressed. The present model is capable of simulating a limited class of tropical cyclones and that often times the "nontypical" storm is of greatest operational concern. If the Navy had followed the warnings of the Central Pacific Hurricane Center for NARDA, Pearl Harbor would have been unnecessarily evacuated, at a cost in the millions of dollars. It is hoped that the Project Meeting will spend a good deal of time discussing ways of improving the initialization and prediction of the tropical cyclone itself.

4.5 OTHER OBSERVATIONS FROM THE 1983 SEASON

NTCM forecast problems related to the synoptic flow were also found in an analysis of 20 cases in the Pacific. The mid and upper tropospheric flow had some effect on the model track, regardless of the true level of large-scale

forcing. There were also several cases in WESTPAC where the model failed to recurve even though the synoptic flow clearly showed recurvature and the storm was actually beginning to recurve. We also observed that the model tended to perform better for developing and hurricane-force storms than for the shallower systems.

4.6 1984 SEASON

NTCM2.0 was run in 1984 and the model was exactly the same as the 1983 version. The only changes involved the schedule and the post-processing as discussed in Section 3.11. This version is called NTCM2.1. In EASTPAC, we also pre-processed the initial conditions using the bias corrector (see Section 3.10). We felt that the persistent nature of the tracks in EASTPAC would benefit from the strong persistence enhancement of the bias corrector. Statistical summarizes will be provided at the Planning Meeting. I am now adapting the EASTPAC and LANT CLIPER models to the FNOC system to make a meteorological comparison as well.

From the statistics that I have so far, I have not been impressed with the performance of the NTCM. The 1984 season had an above-average number of "atypical" storms. Only one hurricane out of the 14 systems in the LANT formed from an easterly wave and that one (KLAUS) occurred in November! Seven out of the 27 systems in WESTPAC formed above 20 N compared to only one such formation out of 23 cases in 1983. The average latitude of formation (latitude of the first warning position) was 14.5N in 1983 vice 16.6N in 1984. This difference might not seem large except that the standard deviation is about 3 deg. The main point is that many of the storms in 1984 were atypical. As stressed many times before, the NTCM has been optimized for more "typical" cases and the 1984 results imply that the present NTCM may have limited utility. Despite the lack of success, the NTCM failures did provide further insight.

4.6.1 SPEED BIAS

The model (NTCM2.1) was very slow in WESTPAC at 48 and 72 h, with speed biases 40% greater in magnitude than in 1983 (based on the statistics to date). The NTCM, and other dynamic models, are known to be slow, so that the 1984 results meant an exaggeration of an already serious problem. The post-processing would occasionally produce short tracks with a "hook" on the end, whereas the storm was observed to be moving at a much greater rate (Fig. 26).

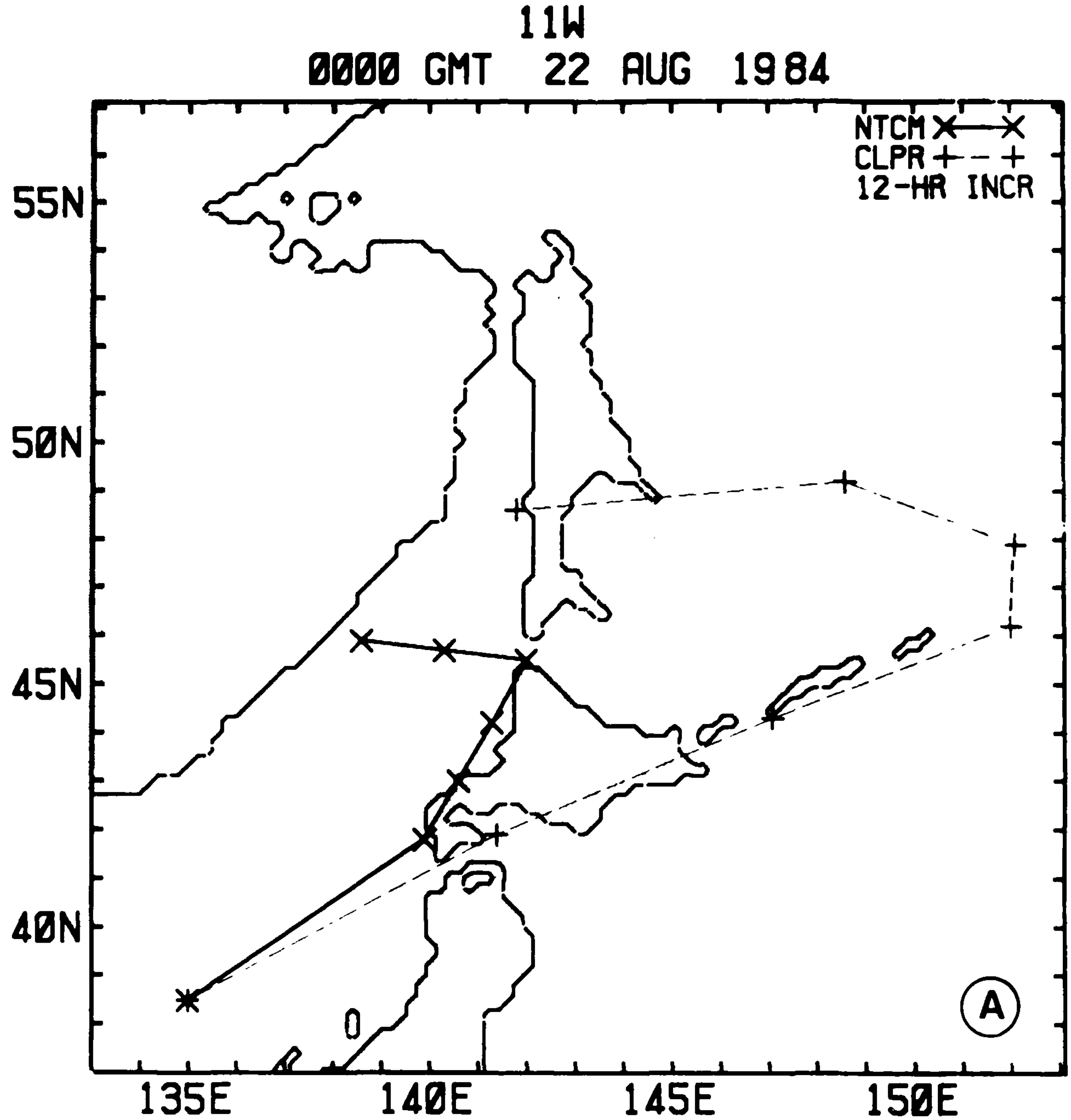


Figure 26. Two examples of how the persistence post-processing distorted the NTCM forecast. Panel A shows Typhoon HOLLY as it recurved through Japan and Panel B Typhoon IKE. The WESTPAC CLIPER forecast is also shown.

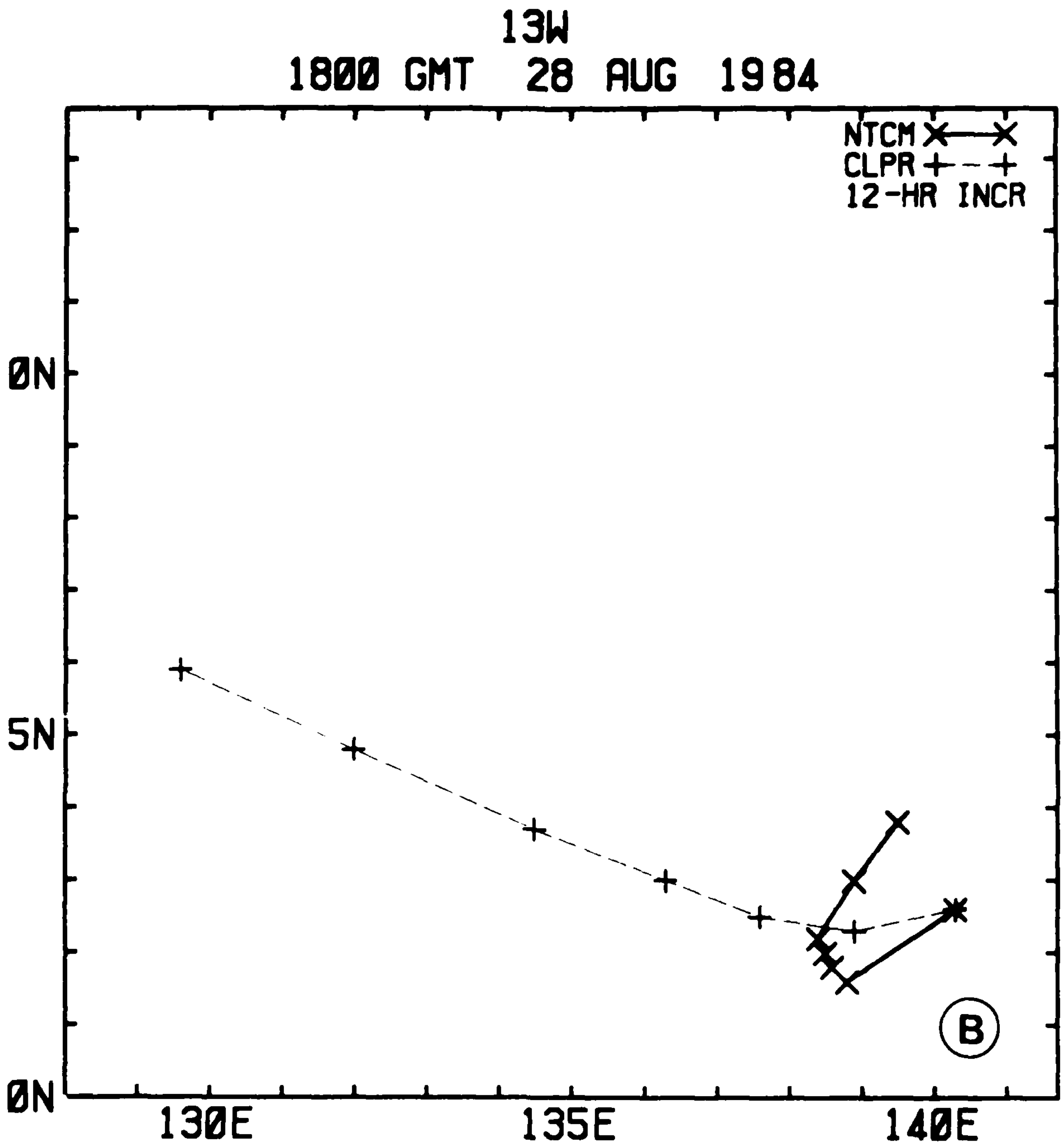


Figure 26, continued.

The best track is not included in Fig. 26 because the charts were produced at FNOC on a real-time basis. The "hooked" tracks were very confusing to the forecasters. In both illustrations, the model tracks were interpreted as a recurvature forecast while CLIPER moves out quite realistically. This experience suggests that the post-processing should be limited when the model motion over the 72 h forecast period is much slower than the observed current motion. *Typhoon IKE was a particularly difficult forecast situation for NTCM* due to what appears to be an analysis problem.

4.7.2 ANALYSIS PROBLEMS

The 00 GMT 30 August 1984 case typified the IKE situation. At this time, IKE was nearly a typhoon with maximum winds of 60 kt. During the following three-day period, IKE intensified into a major typhoon (125 kt) and slammed into the central portion of the Phillippine Islands (PI) causing over 3000 deaths and massive crop and property destruction by flooding. The storm had been moving with a fairly steady heading of 270 deg and 10 kt before the 30th and continued this motion throughout the 72 h forecast period, with some acceleration. The model, however, consistently moved the storm to the north by a few degrees as shown in Fig. 27. The problem can be traced to the initial large-scale flow.

Streamline and isotach analyses of the initial winds on the coarse grid of the two lowest NTCM layers (850 and 550 mb) are shown in Fig. 28. Panel A depicts the circulation of IKE near the center of the grid and the circulation of tropical storm JUNE toward the western boundary. Observations over the PI and China define a very large circulation for JUNE -- on the order of 3000 km in diameter! This large size is also found at 550 mb (Panel B), and the net result is large-scale southerlies to the west of the IKE. Steering arguments would have led to a track toward the north, if the pattern persisted. JUNE was either unusually large, or the FNOC tropical analysis was unrealistic. I suspect the later based on the observed motion of IKE.

Another potential problem is the inability of the model to <u>predict</u> the decay of JUNE during the forecast. In fact, JUNE made landfall and rapidly dissipated less than 24 h after the initial time of the forecast. However, the southerlies to the west had been observed many days before this case. We would have to conclude that both the analysis and the model are at fault -- the analysis for portraying JUNE with excessive size and the NTCM coarse grid model

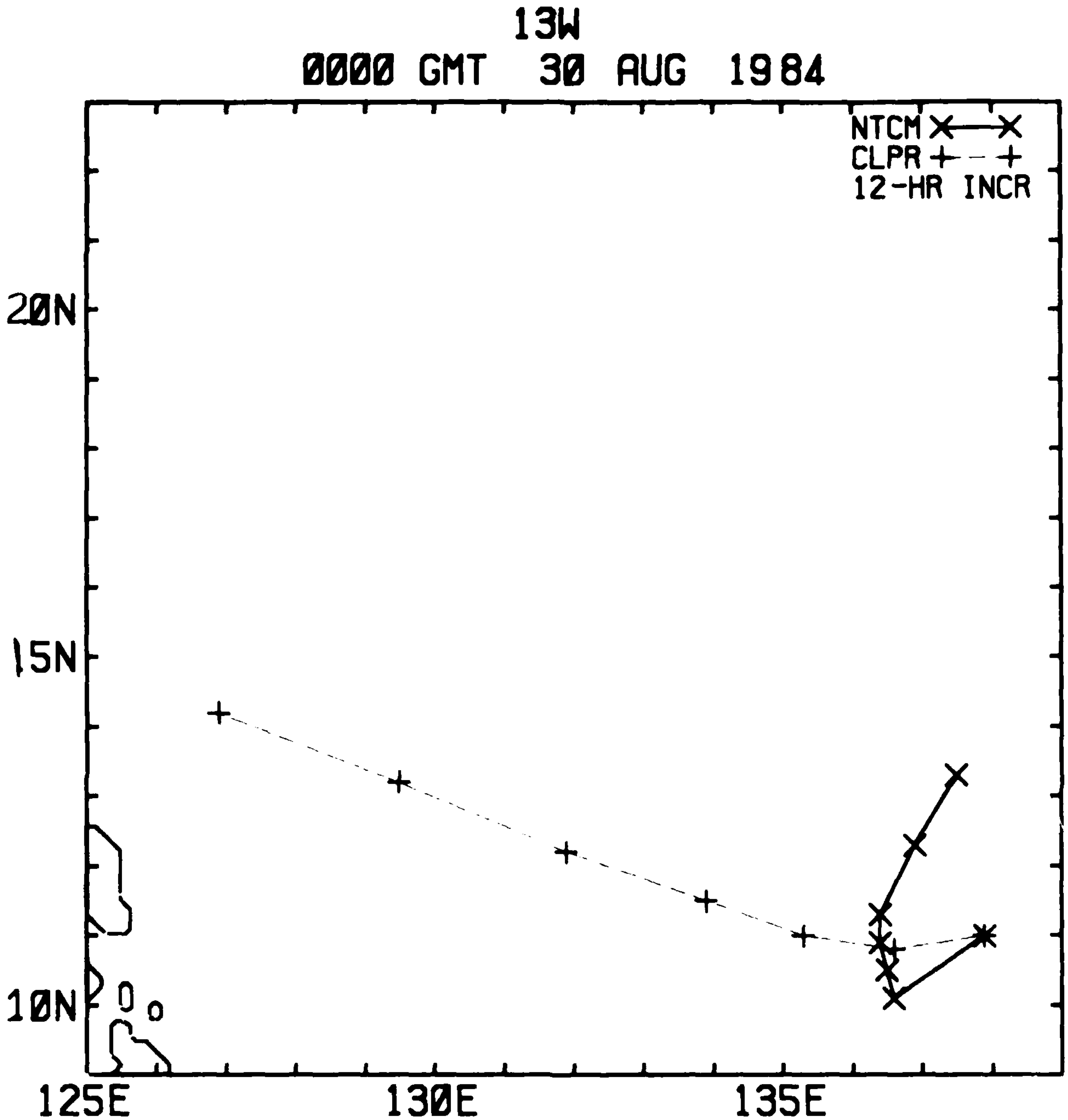


Figure 27. The NTCM post-processed track and the CLIPER forecast for the IKE case.

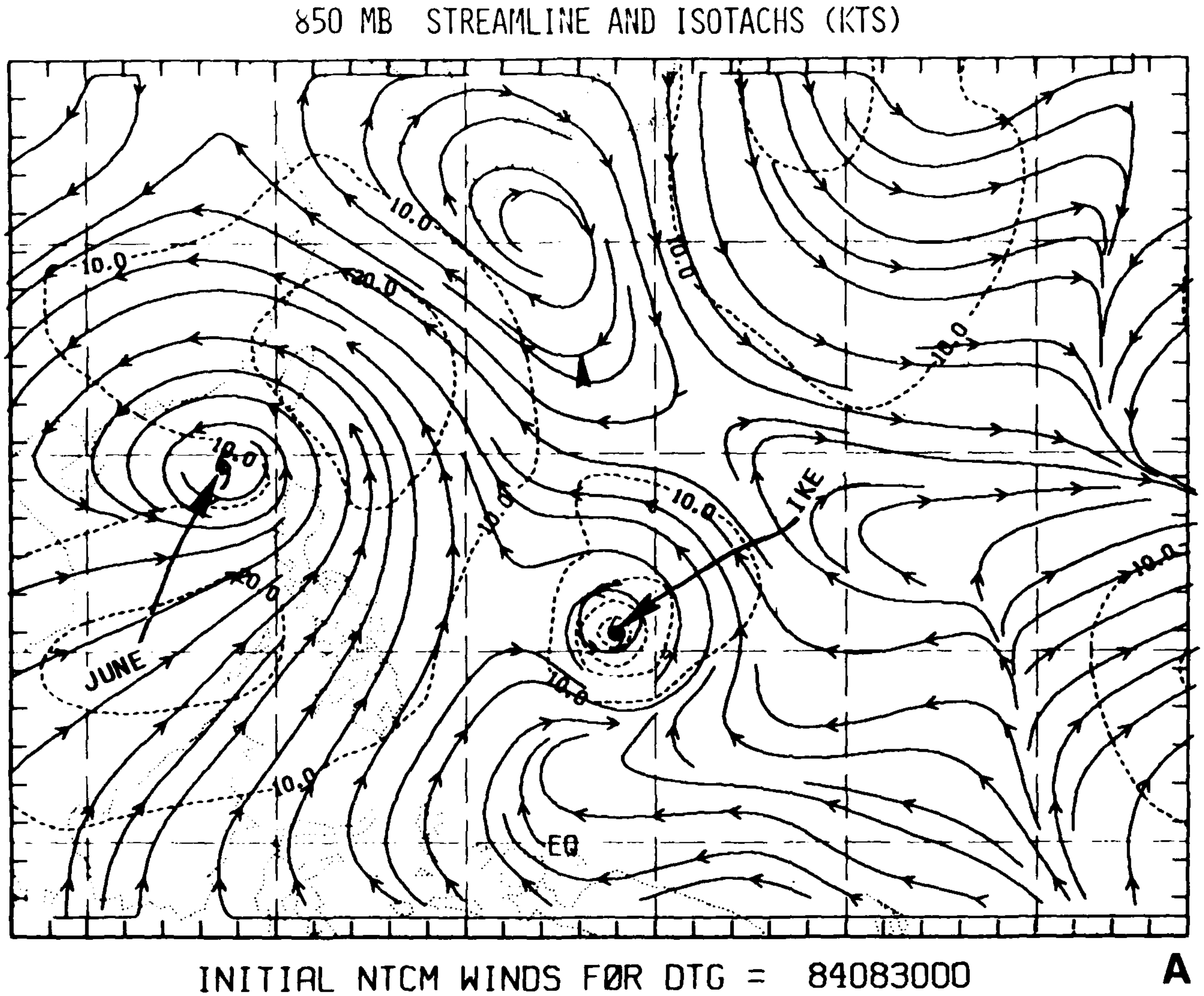
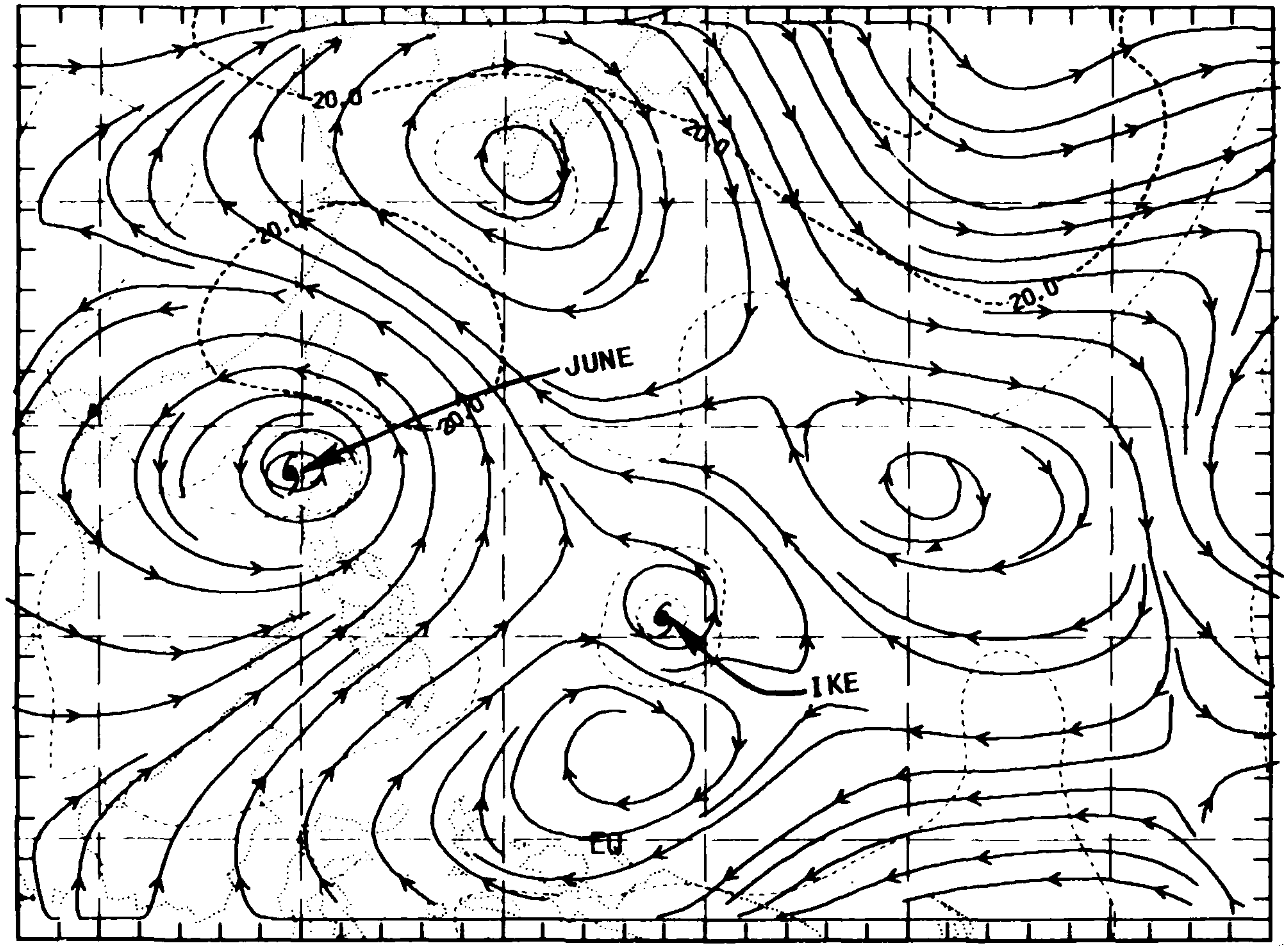


Figure 28. Streamline and isotach analyses of the flow on the NTCM coarse grid at 850 and 550 mb for the IKE case.

550 MB STREAMLINE AND ISOTACHS (KTS)



INITIAL NTCM WINDS FØR DTG = 84083000 **B**

Figure 28, continued.

for not predicting JUNE correctly. Both problems led to the worst forecast errors of the WESTPAC season. The IKE case exemplifies several deficiencies in the current NTCM system. The ATCM system should handle IKE-like situations with more realism and skill.

4.6.3 PERFORMANCE OUTSIDE OF WESTPAC

The bias corrector was very effective in minimizing the speed bias in EASTPAC, but the forecast errors were somewhat higher than in 1983. A comparison with CLIPER is needed to determine if the bias corrector was a good idea.

The LANT was far more active in 1984 than in 1983. However, many of the systems were nontropical and spent most of their existence in the midlatitudes. In fact, the most significant hurricane of the season, DIANA, formed from a cold-core, subtropical storm. Consequently, the NTCM had a poor season in the LANT compared to 1983. The development of the ATCM will have to be guided by the type of system the model is expected to forecast. The NTCM physics and resolution were not capable of predicting many of the LANT storms.

4.6.4 LARGE-SCALE EFFECTS

There were several instances in WESTPAC in which the NTCM failed to predict recurvature by taking the storm south of an approaching trough. These situations were marked by rapid changes in the large-scale flow. One-way influence boundaries could have been helpful, but the inability of the NTCM coarse grid to forecast the environmental changes was a source of many of the large track errors.

Two NTCM forecasts for Typhoon DINAH in WESTPAC exemplify these problems (Fig. 29). At 00 GMT 30 July, the post-processed NTCM predicted the storm to head north initially and then make an almost right angle turn toward the west. DINAH had been in the process of recurvature with steady north-northeast motion during the previous 48 h. The model, however, had been consistently forecasting a westward turn. By 06 GMT 31 July, the NTCM finally predicted recurvature.

The sudden change in the forecast track was caused by a large and unpredicted change in the large-scale flow. Fig. 30 compares the initial 850 and 550 mb flow on the NTCM coarse grid for the two DINAH track forecasts. Because the coarse grid is positioned with respect to the tropical cyclone, the domains of the analyses are slightly different (note the outline of Japan). The most obvious difference in the 850 mb flow (Panel A) occurs north of the storm.

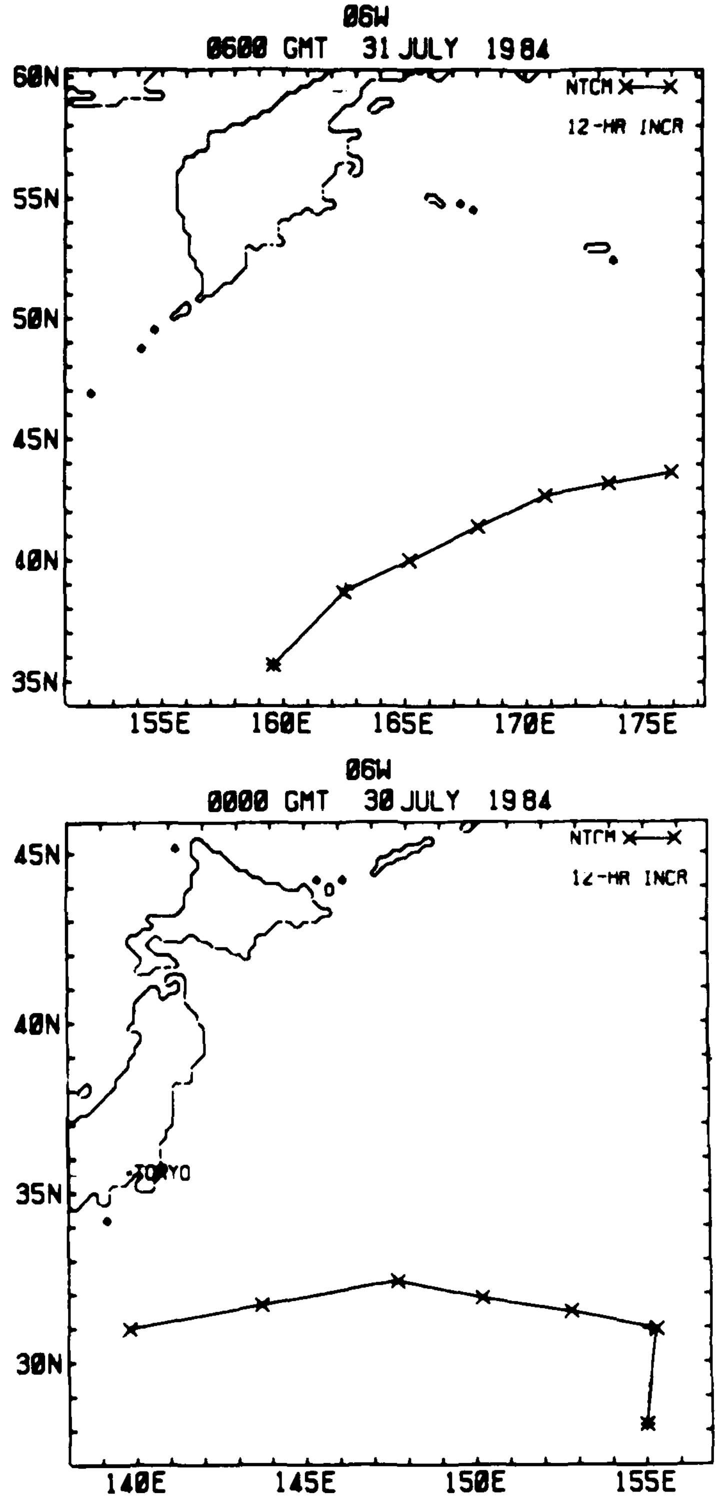


Figure 29. The NTCM-processed tracks for the Typhoon DINAH case.

850 MB STREAMLINE AND ISØTACHS (KTS)

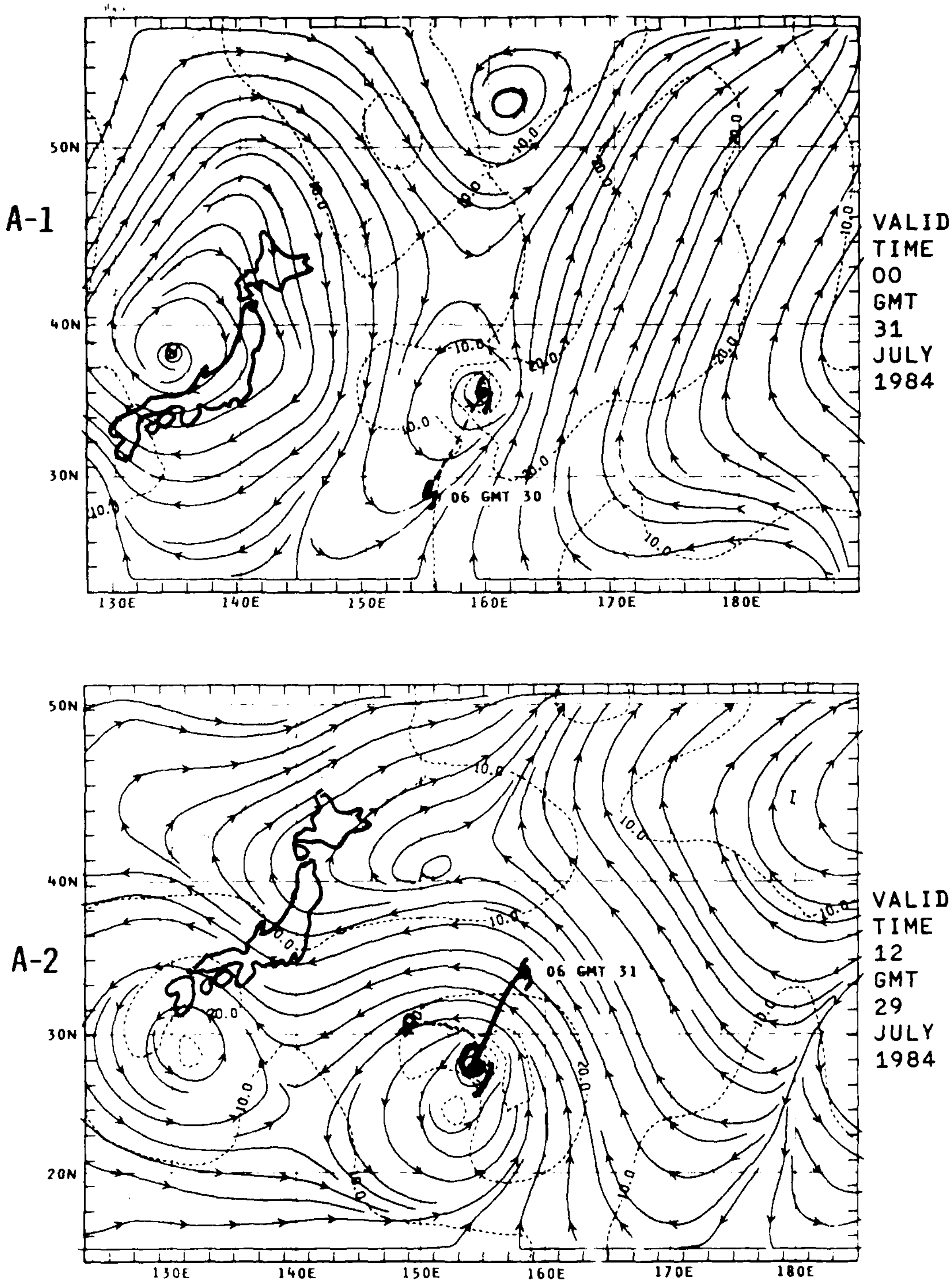
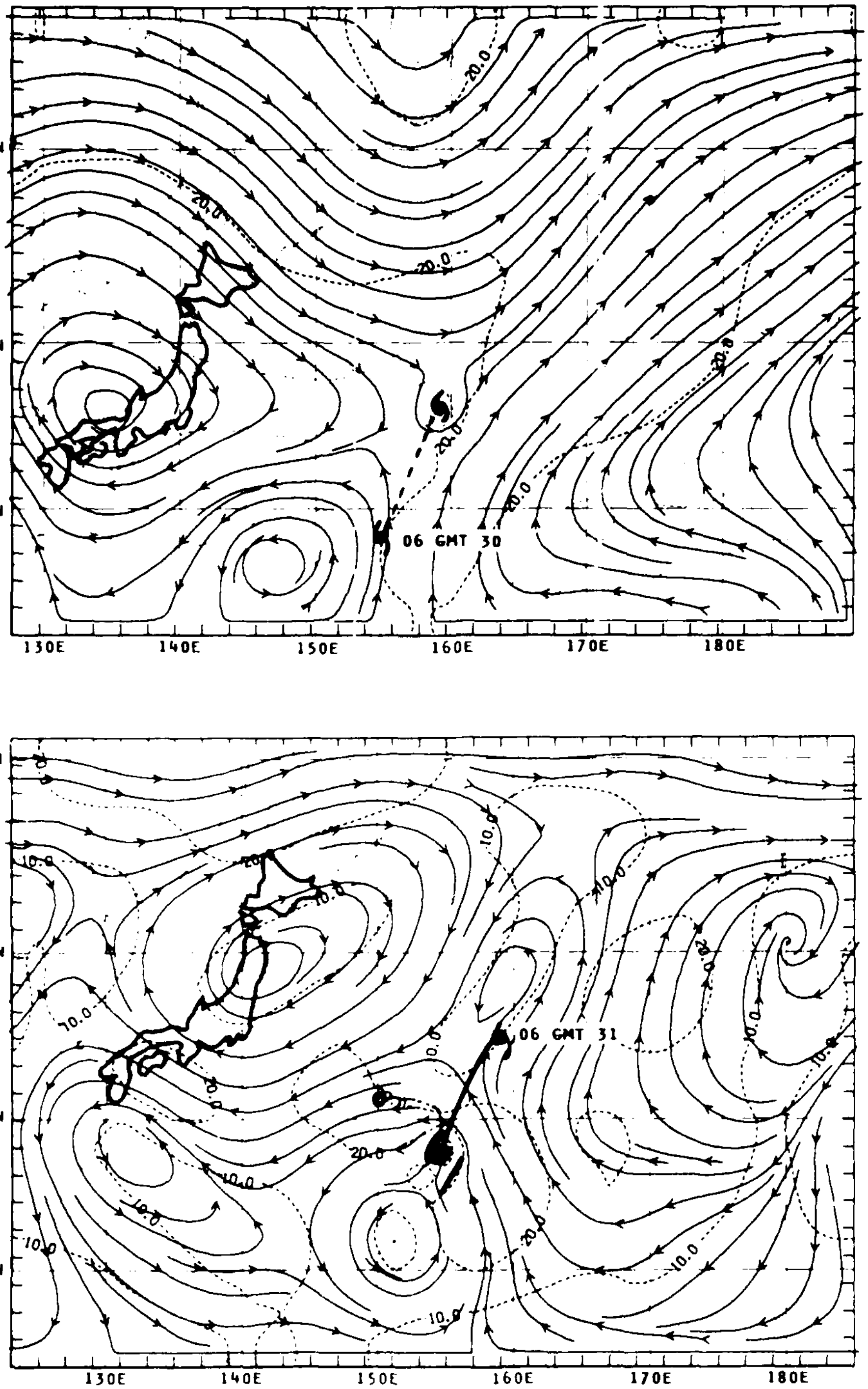


Figure 30. Streamline and isotach analyses of flow on NTCM course at 850 and 550 mb for DINAH case. Dotted track ending with circle in A-2 and B-2 is 30 h NTCM forecast starting 00 GMT 30 July and verifying 06 GMT 31 July. Solid line in A-2 and B-2 shows observed motion during same time period as NTCM forecast. Dashed line in A-1 and B-1 shows previous motion prior to valid time of analysis. (Japan coastline highlighted to aid comparison of flow features.)

550 MB STREAMLINE AND ISØTACHS (KTS)



B-1

VALID TIME 00 GMT 31 JULY 1984

B-2

VALID TIME 12 GMT 29 JULY 1984

Figure 30, continued.

The subtropical ridge environment at 00 GMT 30 July (actually the analysis from 12 GMT 29 July because of the time offsetting) has been replaced by frontal trough pattern by 06 GMT on 31 July (the 00 GMT 31 July analysis) with strong ridging to the west. The 550 mb flow undergoes a similar transformation (Panel B).

There are several important observations about the large-scale flow comparison that should be highlighted. DINAH moved toward the north in repsonse to a "break" in the 550 mb ridge. This response was unusual because the break was to the northeast or "downstream" in the midlatitude synoptic forcing. The model did not simulate this response. However, the 30 h track from the NTCM (the dotted line in Fig. 30) correlated well with the initial flow. Conversely, DINAH moved at right angles to the initial 550 mb flow, which implied a siginificant change in the large-scale environment.

The DINAH case also illustrates a deficiency in the FNOC tropical analysis. A large cyclonic circulation is evident to the southwest of the NTCM bogus position at both 850 and 550 mb. FNOC inserts a bogus tropical cyclone circulation into the surface wind analysis because the observations are seldom adequate to resolve the storm and specify the strong winds around the tropical cylcone needed to properly drive the FNOC ocean wave models. The FNOC tropical upper air analysis procedure is capable of "building" the bogus surface circulation upwards, but only to a limited extent. The FNOC bogussing can also affect the current analysis through the first quess which is derived from the previous 12 h old analysis. The large cyclonic circulation south of DINAH appears to be the remains of the FNOC bogus from the previous analysis, because the circulation is centered very near the location of DINAH 12 h earlier. The NTCM storm insertion is applied on a smaller scale and cannot compensate for the FNOC bogus when it on a scale of about 1500-3000 km.

We have not studied how the FNOC bogussing affects the analysis in detail, but we have observed that the effect varies considerably from one storm to the next and that it is normally insignificant. However, if the FNOC bogus had a greater-than-average influence, we could expect a significant degradation in the skill of the NTCM through a distortion of the initial synoptic forcing. The poor performance of the NTCM in the 1984 season and the large magnitude of the speed bias may be partly attributed to the FNOC bogussing. We are now

considering ways of preventing the tropical analysis from being influenced by the bogussing. One obvious solution is to develop a separate analysis package for the ATCM.

5.0 CURRENT RESEARCH

Unfortunately, the operational version of the NTCM has not performed as well as expected from the research results. The problem areas are related to: 1) the storm simulation; and 2) the forecast of the environment. There is work underway to improve NTCM2.1 in these problem areas.

The first update will be to change the lateral boundaries of the NTCM coarse grid to the one-way influence type as in the OTCM. This change forces the initialization to be modified and in the process I will make the balancing procedure less restrictive dynamically. The net effect of the initialization and boundary conditions changes should be an improvement in the forecast of the large-scale environment.

The second NTCM modification involves the specification of the initial vortex. I will adopt the "spin-up" strategy of NMC in which the initial storm bogus is derived from a previous model integration. In spin-up method, the model is initialized with a weak circulation in a no-flow environment and then integrated until a quasi-steady state is achieved. A series of "spun-up storms" is generated for various initial latitudes and is stored in the form of a "catalog." The latitude of the actual storm determines which vortex is "called up." The advantage of NMC procedure is that the initial vortex will be dynamically compatible with the forecast model. I have generated several NTCM spin-ups and have found large differences between the present bogus storm and the steady-state cyclone supported by the heating (the spin-up). The spin-up will be added to large-scale flow in the same way it was removed using a method patterned after that of Jones (1977). The new vortex initialization should reduce the forecast time required to dynamically "link" the model cyclone to the heating and the environment.

6.0 SUMMARY

The Project Meeting will be divided into three topic areas: 1) data analysis and initialization; 2) numerical aspects; and 3) operational constraints and needs. I will now summarize this review in a point-by-point fashion according to topic areas.

6.1 DATA ANALYSIS AND INITIALIZATION

1) The large-scale analysis affected NTCM skill to a greater degree than any of the model adjustments.

2) The NVA tropical analysis gave better NTCM performance than the global analysis from NOGAPS or from NMC. A global model forecast system may not be the best source of the initial large-scale flow for the ATCM and a separate data analysis and initialization procedure may be required.

3) The balancing procedure can have a large effect on overall performance.

4) Incorporating persistence into the model through an adjustment of the initial winds around the storm can have long-term (72 h), potentially detrimental effect on the forecast track.

6.2 NUMERICAL ASPECTS

1) The long-range skill of the model can be significantly influenced by the vortex maintenance processes of the model.

2) The speed forecast of the NTCM depends on both the large-scale flow and the model.

3) The channel boundary condition do not have a negative effect on the performance of the NTCM.

4) Variation of the map scale factor is not important to the track forecast.

5) The boundary conditions of the model must allow for large changes in the environmental flow if the large-scale component of the dynamic model does not predict such environmental changes.

6) The vortex maintenance and initialization procedures used by the NTCM limits the types of tropical cyclones the model can accurately predict.

6.3 OPERATIONAL CONSIDERATIONS

1) A difference of 6 h between the valid times of the tropical cyclone position and the large-scale analysis will not degrade the overall skill of the model.

2) Simple models can provide forecast track guidance that is comparable to that from more complicated and computational expensive models (e.g., OTCM vs. NTCM and MFM vs. NTCM).

3) Dynamic models often produce tracks with more "detail" than climatological and statistical methods. Post-processing with persistence may be beneficial to short term-skill and model interpretation.

4) Even though the NTCM has been run for over 2000 cases, we are still unable to anticipate the future performance of the model from one season to the next.

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APPENDIX G

STRAWMAN PROPOSAL FOR AN ADVANCED TROPICAL CYCLONE MODEL

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Background

The basic motivation for this planning meeting is to achieve a consensus on developing the next-generation, dynamically based tropical cyclone forecast system. In early planning sessions, it was anticipated that there would be a "run-off" between two or more nested dynamical model candidates. Two obvious candidates were the nested NORAPS and the finite-element model, as both of these models were being tested for regional-scale applications in middle latitudes. External-to-NEPRF candidates might include: the spectral nested model developed at Colorado State University by M. DeMaria and W. Schubert, the nested model at the Hurricane Research Division (NOAA-AOML), the nested model fo the Geophysical Fluid Dynamics Lab, the Movable Fine-Mesh model (or some advanced research version) at the National Meteorological Center, etc.

There are practical and scientific reasons for abandoning the "run-off" strategy. First, there is a requirement to develop a research plan that will provide improved forecast capability at the Joint Typhoon Warning Center within two years or so. Such a timely developmental plan is necessary if it is to receive the endorsement of the DOD community. The scientific reasons center on the perceived importance of the numerical aspects versus the data analysis and initialization (DAI) aspects for improving tropical cyclone track forecasts. It is our judgment that only a small fraction of the present model error is due to inaccuracies in the numerical solutions. By contrast, we feel that improvements in DAI aspects should be given a high priority. With the limited resources available at NEPRF for this task, it is not appropriate to devote 1-2 years to selection, procurement, adaptation and testing of a new dynamical model prior to beginning the DAI aspect.

Basic Strategy

It is proposed that the nested version of the NORAPS be selected as the basic dynamical framework for the Advanced Tropical Cyclone Model (ATCM). In addition to timeliness, the benefit of adopting the nested NORAPS is better

mesoscale (mid-latitude) models. The disadvantage of adopting the nested NORAPS at this early stage is we preclude a possible improvement in accuracy provided by a new numerical technique.

The most basic components in the dynamical model are the advective algorithm and the interface nesting strategy. The first goal in the developmental effort would be to demonstrate that the improvement in numerical techniques alone will provide improved tracks relative to the Nested Tropical Cyclone Model (NTCM). That is, the nested NORAPS with the same initial data, model structure, resolution and physics should provide improved forecasts. If this is true, the nested NORAPS can be adopted as the basic dynamical framework of the ATCM. (Note added after discussions with S. Sandgathe: Given the failure of the NTCM to produce better forecasts than the one-way influence tropical cyclone model (OTCM), it may be necessary to verify that nesting is beneficial in the ATCM.)

The proposed research plan in Table 1 is a "strawman" to facilitate discussion of the strategy and priorities in developing the ATCM. It is intended that a sequence of sensitivity tests (1.1-1.3) be carried out with the basic dynamical model. A second step would be the introduction of improved storm-scale bogus (2.0) and large-scale wind analysis(2.1). The dynamical initialization scheme would also be introduced and tested during this phase (2.2). A third step (3.0) would be to predict the latent heat release in response to dynamical forcing, which would replace the fixed analytic heating distribution of the present NTCM. A planetary boundary layer parameterization must also be introduced at this time. Furthermore, an explicit treatment of moisture is required. In the first stage, the initial moisture field would be derived from the previous 12-hour forecast. The next stage (3.1) would be to analyze the relative humidity, which would require observations within the tropical cyclone. On a lower priority (3.2), other latent heat parameterizations would be tested. Finally, the lowest priority (4.0) is given to introducing topography for prediction of the interaction of the tropical cyclone with islands or other land features.

Table 1. Proposed research plan for developing and testing various components of the Advanced Tropical Cyclone Model.

Version	
1.0	Configuration as in present Nested Tropical Cyclone Model*
1.1	Triply-nested version, testing effect of horizontal resolution (possibly 25, 75 and 225 km grids)
1.2	Increased vertical resolution (about 10 levels)
1.3	Horizontal diffusion within inner grid (fourth, sixth order)
2.0	Improved storm bogus within inner grid, realistic wind structure and blending with large-scale flow, amplitude related to present storm characteristics
2.1	Regional objective analysis for winds (optimum interpolation)
2.2	Initialization (nonlinear vertical mode or normal mode)
3.0	Introduce latent heating parameterization (Kuo) and planetary boundary layer
3.1	Regional objective analysis of relative humidity (rather than previous forecast of humidity)
3.2	Test other latent heating parameterizations
4.0	Introduce topography

*NTCM characteristics: Fine-mesh grid, 41 km; coarse-mesh grid, 205 km; three pressure layers of 300 mb; analytic heating pattern following storm center; no moisture fields; no planetary boundary layer; channel boundary conditions on coarse grid; simple storm bogus within entire fine grid.

APPENDIX H

PRELIMINARY ISSUES FOR ALL GROUPS

Note: These issues were developed by the meeting chairpersons and are only suggestions. We welcome deletions, modifications and/or additions. There will be three individual group discussion periods (see schedule). The issues have been grouped according to the schedule.

GROUP DISCUSSION SESSION 1

1.1 Short-term motion is known to be persistent. Should we attempt to force persistence into the dynamical model forecast via the initialization? If so, how? By steering methods (bias-corrector) or by dynamical techniques such as dynamic initialization by nudging?

1.2 What domain size(s) should be used to handle multiple storm situations in the NW Pacific? What strategy for data analysis, initialization and the numerical model integrations for multiple storms?

GROUP DISCUSSION SESSION 2

2.1 According to JTWC, the forecast can be received as late as 6 h following synoptic time. Can the analysis/forecast procedure be shifted closer to synoptic time to take advantage of more recent synoptic data (vs. using prior 12 to 18 h prog fields)?

2.2 When in the operational cycle will the ATCM be run? Will it rely on boundary conditions from another model? If so, will it be a previous model run?

PRELIMINARY LIST OF ISSUES FOR THE NUMERICAL ASPECTS GROUP (NUM)

GROUP DISCUSSION SESSION 1

1.1 Is there general agreement that the potential reduction in track errors from improved numerical solution methods is small relative to other error sources? Would the potential error reductions from other than the nested NORAPS (see strawman) justify the delay in the selection and testing of such a model?

1.2 Would a two-way nest in a global model, i.e., a combination of the best vortex simulation and the best environmental simulation, produce better forecasts? If so, by how much?

1.3 Can point steering at each level in the ATCM be used to determine the steering level? Are these steering forecasts useful in model diagnosis? (together with OP)

GROUP DISCUSSION SESSION 2

2.1 One of the goals of this meeting is to obtain a consensus on the most advantageous solution to the ATCM track model. Rank and discuss the contributions of each numerical aspect to the accuracy of the track forecasts (e.g. should more resources be devoted to vertical representation vs. time differencing, etc.). What are the relative merits of: 1) various nesting strategies; 2) horizontal spatial representation (second- vs. fourth- order finite differences, finite elements, spectral); 3) vertical representations (finite differences vs. finite elements, sigma vs. pressure, hybrid); 4) time differencing (spite explicit, Lax-Wendroff, etc.)?

2.2 What percentage of the computer resources should be allotted to advective (dynamical) aspects vs. physical processes? In summary, what is likely to be the optimum configuration of the ATCM?

2.3 Is a dynamical model capable of predicting the interaction of tropical cyclones with TUTT lows, monsoon trough depressions, cut-off lows, etc.? What vertical and horizontal resolution over what domain size would be necessary?

2.4 A negative speed bias tends to reduce forecast error, but forecasters are required to make track predictions with typical speed. How can the ATCM be designed to insure the system always makes a "forecast" or produces track lengths that is approximately the same as observed?

2.5 Can the ATCM forecast be used to diagnose track type (e.g. loopers, stallers, straight runners, recurvers, etc.)? (together with OP)

2.6 Will an ATCM that is "tuned" to the NOGAPS analysis give as good a result as if it were tuned to the NVA analysis? (together with DAI)

2.7 Would greater skill be derived from an improved vortex-scale or large-scale simulation? What is the relative contribution of each type of simulation to the ATCM track accuracy?

GROUP DISCUSSION SESSION 3

3.1 Is a true interaction between dynamics and physics a necessity for a realistic simulation of the vortex structure, or are analytically specified heating approaches adequate, particularly in the context of what data are currently available to define the storm and large-scale flow? The boundary layer is intimately tied to the convective processes and has been shown to be of some importance to motion as well. If simple vortex simulation treatments are used, how much effort should be placed in a boundary layer parameterization?

3.2 Discuss methods to assess sensitivity to: 1) horizontal and vertical resolution; 2) vortex simulation, including heating and initialization; 3) orography and the boundary layer; and 4) boundary conditions on the outermost grid.

3.3 What types of sensitivity testing for the cyclone problem will be necessary with regard to the analysis? (together with DAI)

3.4 What numerical considerations/research programs are necessary to achieve the goal of predicting the influence of topography on the tropical cyclone?

3.5 What is the optimum strategy for the boundary conditions in the numerical model? On the outer grid, the inner grid? Analysis phase and the prediction phase? (together with DAI)

PRELIMINARY LIST OF ISSUES FOR THE DATA ANALYSIS AND INITIALIZATION GROUP (DAI)

GROUP DISCUSSION SESSION 1

1.1 How will regional analysis and initialization routines be related to the global system? Will there be re-analysis for the regional grid? In this aspect, the timeliness of the operational tropical cyclone forecast is crucial.

1.2 Is it better to use a "stable" analysis procedure or a superior, but constantly modified analysis (An everchanging model/analysis system gathers no MOS)?

1.3 Are the global model short-term predictions and the presently available initialization techniques sufficiently advanced that a 4-D data assimilation would be effective in the tropics in general? In tropical cyclone regions? For the tropical cyclone itself?

1.4 Should "drawing closely to the observations" be emphasized over "assuring dynamical consistency?"

1.5 Should storm-scale and large-scale analyses be done simultaneously? Should a storm-scale analysis be a re-analysis on a fine grid with the first-guess field from the large-scale analysis or the ATCM analysis/forecast itself?

1.6 Are there adequate observations to analyze TUTT lows, monsoon trough depressions, cut-off lows and other tropical and subtropical phenomenon within the JTWC area of responsibility?

1.7 Should the separate analysis procedures for the tropical cyclone and the large-scale be maintained in the ATCM era?

1.8 Which of the three NOGAPS fields should be used to provide the large-scale flow for the ATCM? Should we even use NOGAPS?

1.9 How will changes from the variational balancing/analysis to OI in NOGAPS affect the development of the ATCM?

GROUP DISCUSSION SESSION 2

2.1 Will an ATCM that is "tuned" to the NOGAPS analysis give just as good a result as if it were tuned to the NVA analysis? (together with NUM)

2.2 Discuss the availability and relative contributions to accurate track forecasts of the various types of observations in and around tropical cyclones. This discussion should take into account differences between tropical cyclone basins.

2.3 What analysis and initialization procedures would make optimum use of the mix of observations that are likely to be available?

2.4 If sophisticated convective parameterizations and PBL representations are to be used, what special analysis and initialization procedures are required? What type of specific humidity analysis is possible?

2.5 What analysis procedures (OI, successive correction) should be used for the ATCM system? Over what domain? Should the resolution be specified differently for large/small cyclones? What fields (wind or mass) should be emphasized?

2.6 Is it necessary to have a climatological component in the ATCM analysis? If so, what type of climatology, global model or observed?

GROUP DISCUSSION SESSION 3

3.1 What satellite systems are available/planned and what variables will be sensed, with what accuracies?

3.2 How will the inner region (storm) data be specified? Will the inflight transmission of reconnaissance data be incorporated?

3.3 Should we move forward with dynamic initialization procedures, or should we stick with the static methods of initialization as is currently done in the operational tropical cyclone models?

3.4 Should a high-resolution global model be used to generate high-resolution "data" for data-deprivation studies?

3.5 Discuss the possibility of applying the empirical orthogonal function approach to the current operational wind analysis in order to determine which features (as opposed to scales) of the large-scale flow have the greatest impact on the ATCM forecast.

3.6 Considering the vertical distribution of tropical data, how many levels should be used? How can information at primary data levels be extrapolated to adjacent levels?

3.7 What are the advantages and disadvantages to limited-area prediction models of nonlinear vertical normal mode initialization? Interpolation from global nonlinear normal mode initialization (can this be done just to support the tropical cyclone forecast problem)?

3.8 How can the data analysis procedure be designed to handle the genesis of small intense cyclones with the 12 h cycle.

3.9 Would persistence of the observations in the ATCM analysis be beneficial?

3.10 What special data analysis considerations should be given to handling the dramatic differences in data availability from region to region?

3.11 What types of sensitivity testing will be necessary for the cyclone problem, particularly with regard to the analysis? (together with NUM)

3.12 What strategy for boundary conditions in the numerical model should be used? On the outer grid, the inner grid? Analysis phase and the prediction phase? (together with NUM)

PRELIMINARY LIST OF ISSUES FOR THE OPERATIONAL GROUP (OP)

GROUP DISCUSSION SESSION 1

1.1 Does the operational group endorse or differ with the pre-planning document as to the following items: 1) The desirable operational characteristics of an ATCM; 2) Importance/priority of tropical cyclone basins; 3) optimum time slots for the forecasts to arrive; and 4) priority given to multiple storm situations?

1.2 What specific aspects of the ATCM prediction will be transmitted?

1.3 Should there be model output type statistical post-processing?

1.4 What initial data and prediction variables will be archived?

1.5 Are there diagnostic variables that should be calculated for use in interpretation of the predictions?

1.6 Our feeling is that tropical cyclone track prediction accuracy is a function of: 1) storm-related factors, such as size and intensity; 2) environmental factors, such as vertical shear and surrounding synoptic features; and 3) data accuracy. How can the impact of these factors be taken into account in the design, interpretation and transmittal of the ATCM?

1.7 JTWC tends to use the dynamical forecast models as an "integration of the environmental wind fields" rather than as the primary objective aid. Should the ATCM be designed to achieve that goal or as the primary forecast tool (which is only slightly and/or infrequently altered)?

1.8 What are the appropriate measures of "goodness" for evaluating different ATCM configurations? What sample size, kinds of storms, etc. is required for a definitive test of the dynamical model?

1.9 Should 96 h forecasts be generated routinely for NW Pacific?

1.10 Other objective aids are run in a "background" mode for tropical systems prior to the time of the initial warning so that some track guidance will be available if required. Can/should the ATCM also be run in a "background" mode?

1.11 How can "forecast content" be assessed for a research model? What are appropriate measure of consistency in track forecasts?

1.12 Should the separate analysis procedures for tropical cyclone and the large-scale be maintained in the ATCM era? (together with DAI)

1.13 Which of the three NOGAPS fields should be used to provide the large-scale for the ATCM? Should we even use NOGAPS? (together with DAI)

1.14 How will changes from variational balancing/analysis to OI in NOGAPS affect the development of the ATCM? (together with DAI)

1.15 What special data analysis considerations should be given to handling the dramatic differences in data availability from region to region? (together with DAI)

1.16 Can point steering at each level in the ATCM be used to determine the steering level? (together with NUM)

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